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Applications of Aerospace Technology in Industry

A TECHNOLOGY TRANSFER PROFILE

LUBRICATION

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APPLICATIONS OF AEROSPACE TECHNOLOGY IN INDUSTRY

A TECHNOLOGY TRANSFER PROFILE

LUBRICATION

- Prepared for -

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- Prepared by -

Industrial Economics Division
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PROFILE HIGHLIGHTS

NASA engineers have produced significant innovations in lubrication technology to satisfy performance and reliability requirements. These contributions have created a new state-of-the-art for many phases of lubrication during extreme operating conditions such as very high or low temperatures, large ball bearings at high speeds and heavy loads, vacuum, zero gravity, high reliability for extended use and great stability. They include new dry film lubricants and methods for applying dry lubricants, testing and evaluation of lubricants and lubricating methods to generate necessary data, new metallurgical techniques for improved bearing surfaces and new lubricating methods. Industrial applications of this technology are just beginning as design engineers realize the extent to which the frontiers and limitations formerly imposed by lubrication and bearings have been moved forward with NASA research.

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INTRODUCTION

The field of lubrication has been selected for special examination in this presentation because it provides a convenient vehicle for describing the complex and important processes of technology transfer. The flow of technology from its point of origin to its ultimate, widespread applications is dependent in special ways upon the nature of user needs. This document attempts to trace the early phases of the movement of NASA-generated lubrication technology into the private sector as affected by evolving industrial requirements.

This presentation underscores the pioneering efforts of NASA in developing design alternatives with substantial promise for future applications across an entire spectrum of industries and markets. The lubrication field, in particular, is one where NASA has made substantial technical contributions to the design of systems operating in extreme environments (e.g., high temperature). The promise of the contribution lies in extending the operating life of mechanical systems under less extreme conditions as well as in charting the design path for totally new applications.

This profile of the lubrication field considers its technical basis, the industry supplying the materials of lubrication, and certain "user" industries that demand both materials and lubrication technology in order to meet their product requirements. Section I presents an overview of this field, while Section II describes certain NASA technical contributions to lubrication technology which will have a lasting impact in the solution of specialized lubrication problems. Section III reviews mechanisms used by NASA to communicate a wide variety of technical advances, and Section IV summarizes specific examples in which these technologies have been utilized in the private sector. Finally, Section V summarizes certain important factors related to the transfer of NASA-generated lubrication technology.

SECTION I. AN OVERVIEW OF THE LUBRICATION FIELD

The real complexity of the lubrication field can be partially grasped by considering the multidisciplinary aspects of the technology involved. The physicist, the chemist, the metallurgist, and the engineer are all involved in lubrication research. Indeed, the lubrication industry reflects this same complexity. An examination of the field's industrial base shows that a variety of industries are involved and that each makes a special contribution to the technology as well as to the market place. The common denominator for both the industry and the technology is extending the life of mechanical systems. The production of lubrication materials constitutes one of the largest industries in the world. Despite consistent advances made in the field, a considerable amount of all energy produced is still lost to friction. Hence, interest continues to be strong in preserving and extending the performance and life of mechanical systems.

Animal fats and oils were the primary lubricating materials until the mid-1800's. When the first oil well was drilled in Titusville, Pennsylvania in 1859, however, the technology of lubrication quickly assumed commercial importance. By the mid-1930's, the performance demands outstripped the basic properties of petroleum oils and new synthetic additives were introduced. Those additives were used to increase the load carrying capacity, lubricity, corrosion protection, and thermal stability of oils. Today, according to Industry Week (July 27, 1970, p. 41), the petroleum industry in the United States provides lubricating oils and greases worth more than $500 million annually. This amounts to approximately two percent of the value of petroleum products produced. Some 48 U.S. refineries produce more than 200,000 barrels of lubricating oils and greases each day.

The production of lubricants, however, is only part of the story. The bearings industry, which is tied closely to the consumption of lubricants, also is economically significant. The estimated value of bearings shipped during 1970 exceeded $1.4 billion according to recent industrial profiles prepared by the Department of Commerce (U.S. Industrial Outlook, 1970, p. 280). The production of both lubricants and bearings has essentially doubled over the last 12 years.

These two industries are related because their respective products are always combined in the operation of a mechanical system, be it an automobile engine, a power plant or an electric typewriter. Their relationship, however, is actually more fundamental. The cornerstone

of mechanical design is always performance and reliability: lubrication and bearing technology directly control both performance and reliability. Bearing design usually dictates the appropriate lubrication principle; however, improving bearing performance is as much a product of lubrication technology as it is bearing technology. This relationship is evident in the following example drawn from NASA experience.

Elastohydrodynamic (EHD) lubrication occurs in gears and ball bearings even when solid parts of a system make sliding contact (e.g., between the balls and the inner race of a ball bearing). It has been found, however, that there is still a thin film of lubricant (the EHD film) that lubricates the "contacting" surfaces. The thickness of the film and the distribution of pressures in the zone of near contact are dependent on both the hydrodynamic properties of the lubricant and the deformation of the bearing surfaces in the same region. Hence, the material properties of both the lubricant and the bearing are critical to performance. The importance of the bearing properties was demonstrated in one research program in which NASA scientists were studying the effects of material hardness in an EHD application. It was discovered that, under given lubricant conditions, the fatigue life of a ball bearing is dependent on the hardness differences between the balls and the inner race and that relative bearing life could be extended through precise control of the hardness differences (Zaretsky and Anderson, 1968).

Lubrication technology has been classified in many ways through the years. One approach has been to classify lubricants by their state (i.e., liquid, solid or gas) and this of course matches the major industrial classifications. Liquids, including oil and greases, comprise the lion's share of the industrial market, with automotive and aviation applications providing the largest consumption. Another approach is to classify lubricants by the operating characteristic of the bearing: "thin" film or boundary lubrication encompasses all three lubricant states and differs from "thick" film lubrication in that the surface asperities of the bearing can and do contact through the lubricating medium. Each of these approaches is useful in tracing the dramatic increase in the amount and type of lubrication research undertaken by universities, industrial firms and government agencies. The American Society of Mechanical Engineers recently published a literature review, <u>Boundary Lubrication: An Appraisal of World Literature</u> (Ling, Klaus, and Fein, 1969), which identifies significant research studies conducted from 1920 to 1965. From 1920 to 1954, a yearly publication average of 15 books or articles were abstracted; from 1955 to 1961, the annual average increased to 85;

and from 1962 to 1965, the average reached 100 items per year. Much of this heightened research activity centered around developing concepts and data that could be useful in meeting high performance lubrication needs. Higher speeds, heavier loads, and higher operating temperatures in all kinds of machinery, operating under increasingly demanding environmental constraints, reflect the types of areas researched.

Developments in liquid lubricants have moved somewhat slower than in the solid and gas classifications because liquid materials are the mainstay of present applications. The solid and gas lubricants are found in the "new" and "future" applications, and as a result, technical advances seem more dramatic. The trend toward higher performance and smaller power packages generates development in all three areas. For instance, in a forecast of new motor oil blends prepared for the Journal of Commerce (June 18, 1970, p. 10), an industry analyst predicted the development of new blends of motor oils that will result in improved performance under high temperature conditions. The analyst claimed that automotive engine oils have been subjected to higher temperatures in recent years due to leaner air/fuel ratios; sustained high speeds on interstate highways; increased hauling of trailers and boats; and wider use of automatic transmissions, air conditioners and other accessories. Pointing out that damaging aftereffects of high temperature operations can be minimized by varying the blending stocks of motor oil, the analyst noted that both the automotive and petroleum industries are now investigating various solutions to the problem.

As if to demonstrate progress made to date in dealing with the high temperature lubrication problem, a later issue of the Journal of Commerce (August 11, 1970, p. 6) reported that the Shell Oil Company has introduced "Super Shell 10W-40," a new multi-grade motor oil replacing its "10W-30" grade. The oil combines all the features of the "10W-30" oil and adds a wider viscosity range for increased engine protection when operating at higher temperatures under severe driving conditions.

Three basic trends can be identified in the recent growth of the petroleum industry. There is a growing demand for high quality lubricating oil; the demand for industrial lubricating oil is increasing more rapidly than that for automotive uses; and there is increasing demand for specialized products (e.g., air bearings and solid lubricants). Specialized products are directly tied to the advances in the technology of lubrication and are of particular interest in this overview. The nature of NASA contributions to the technology and the need for special

products have the common goal of achieving higher performance under extreme conditions.

Two specialty products of exceptional significance are molybdenum disulfide greases and fluorocarbon resins. Molybdenum disulfide is a solid lubricant often combined with a grease to achieve "permanent" lubrication for such applications as the automobile chassis and differential. The Climax Molybdenum Company in Golden, Colorado reports that the world consumption of this lubricant is approximately 100 million pounds and is growing at seven percent annually (Fitzsimmons, 1970). The market for fluorocarbon resins, principally the Teflon family, which includes such applications as bearings, bearing pads, seals, rings, valves, and dry sprays, is estimated at $30 million annually by a Du Pont representative (Purinton, 1970). These two examples show that conventional lubricants now have important competition in the area of special applications. Both of these lubricating materials were mere curiosities 20 years ago.

Solid lubricants have enjoyed systematic development only in the last decade. With the introduction of supersonic aircraft and spacecraft, more severe temperature and pressure conditions increased the need for solid lubricants. Solid lubricants have the advantage of good stability at extreme temperatures and in chemically reactive environments. They afford the design advantage of lighter weight, simplification, and improved dynamic and mechanical stability. These lubricants open up new frontiers in operating machinery, not only under high temperatures, but also under conditions of extreme cold, very high vacuum, nuclear radiation and extreme loads.

Section II of this presentation examines some of the ways NASA research has contributed to the technology of lubrication in extreme environments.

SECTION II. REPRESENTATIVE NASA CONTRIBUTIONS TO THE LUBRICATION FIELD

Three specific areas of NASA contribution to the field of lubrication are presented in this section: the formulation of new lubricants, the development of methods for applying lubrication, and the devising of new ways of testing and evaluating lubricants. It must be emphasized that these contributions do not begin to adequately represent the total body of developments in the field that have resulted from NASA-sponsored research. Lubrication is such a complex field that an attempt to describe NASA contributions that have occurred in all areas dealing with lubrication is far beyond the scope of this presentation. Instead, a very select number of developments which are important in their own right but also typify the work that NASA has made have been chosen. A brief review of NASA contributions in this field reveals that many of them have certain common characteristics. First, most of the developments provide answers to real world problems or anticipated problems requiring practical solutions. Second, because NASA's own problems are often unusual, their answers have also tended to be unusual. In Attachment II, these contributions are discussed in somewhat more detail as well as a number of other NASA developments of a similar nature.

NASA has had to deal in extremes that range from the numbing cold of liquid oxygen to the searing heat of a rocket exhaust, and from the enormous weight of a rocket on a launch pad to the weightlessness and extreme vacuum of outer space. In all of these cases, there have been parts that have required lubrication in a manner that guaranteed very high reliability. Adequate solutions often could not be found in traditional methods or materials; new ones had to be found. The result has been developments that are on the frontiers of knowledge in this field. This very fact means, however, that most of these developments are yet to have a large impact on the work-a-day world of lubrication. They provide answers to questions that most people have not yet asked.

It is apparent that NASA's concerns -- lubrication at extreme temperatures, at high speeds, under extreme loads, and with a very high degree of reliability -- are becoming the concerns of an increasing number of industries as well. Electric motors are being designed to operate at hundreds of degrees above room temperature. The development of high speed computers has been made possible, in part, by a stable lubricating film of air between a recording head and a tape or disc moving at high speeds under conditions demanding extremely close tolerances. High speed ground transportation will require lubricants

that will function under a variety of severe conditions. Figure 2-1 depicts the trend toward higher speeds and higher temperatures for bearings used in jet aircraft.

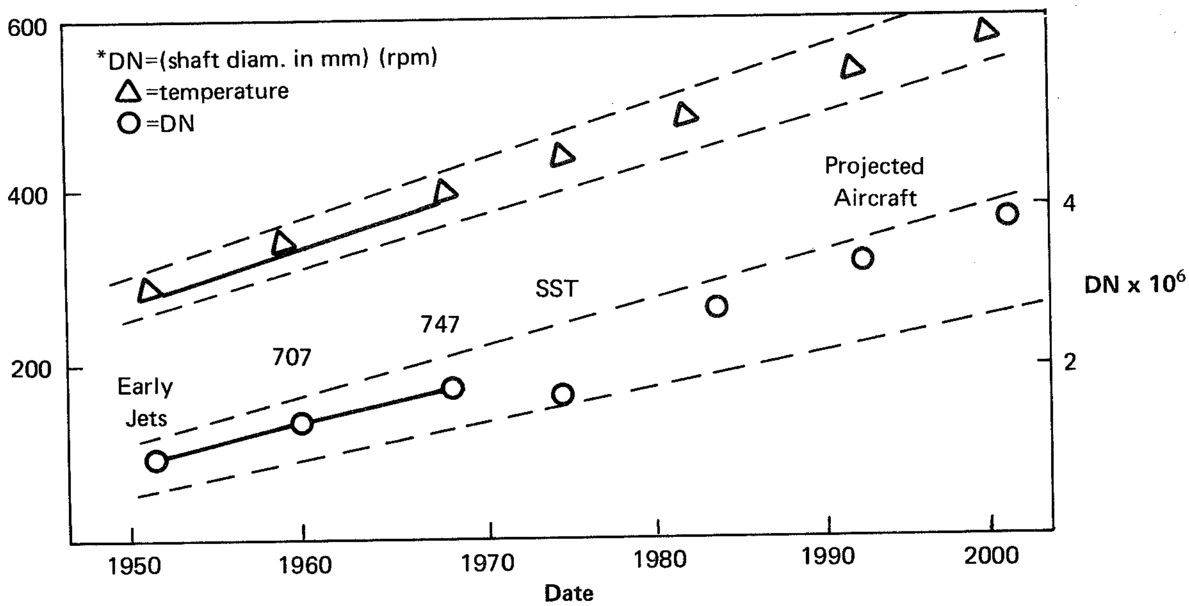

Figure 2-1. Temperatures and DN Values* of Mainshaft Bearings for Commercial Jet Engines (Projected to the Year 2000).

In addition, novel lubricating techniques or materials developed for a limited time use under severe conditions may provide lubrication for extremely long periods of time under more normal conditions. A good example involves a novel use of alloys and composites originally developed by NASA scientists as bearing materials in situations where lubricants could not be used. The alloy itself, because of its crystal structure, has self-lubricating properties and does not cold weld in the extreme vacuum of outer space. These same types of alloys are now being evaluated for the hip joint of artificial legs, a situation where long bearing life is essential and conventional lubricants cannot be used.

Many of NASA's developments possess the dual quality of being able to satisfy lubrication needs under conditions that are rarely encountered in most industrial applications, yet also offer the potential of providing increased life or reliability under less severe circumstances.

The three developments to be discussed are quite different from each other. In one case the contribution is a new lubricating material; in another, new and improved ways of forming solid lubricant films; and in the third, the evaluation and testing of fluids for use as high temperature lubricants. Each development is important because it represents a state-of-the-art contribution that has permitted scientists concerned with lubrication problems to raise their sights to a higher level in these particular areas. All three have the common thread of having been developed to achieve lubrication under severe or unusual conditions.

Metal Fluoride Salts as High Temperature Lubricants

Heat is very often associated with bearing failure. With improvements in metallurgy and fabrication techniques for bearings, failure in most cases is due to an inability on the part of the lubricant to provide adequate lubrication as the temperature is increased, rather than a thermal deficiency of the bearing itself. Because higher speeds, increased loads, and higher engine temperatures mean higher bearing temperatures, engineers are continually seeking lubricants with improved high temperature properties.

A number of approaches have been taken to satisfy this need. Fluids with greatly improved thermal and oxidative stability have been developed. Very pure hydrocarbon oils, aromatic polyethers, and fully fluorinated polyethers are among the most promising.

A second approach has been to use solids rather than liquids as lubricating materials. Molybdenum disulfide and graphite are the two most commonly used solid lubricants. They offer the advantages of low volatility and increased thermal stability when compared to liquids. For example, Vitrolube, a commercially available, ceramic bonded dry film lubricant, which utilizes a mixture of molybdenum disulfide and graphite, provides relatively long term lubrication up to about 700 °F and can be used for shorter periods of time at even higher temperatures. Most liquid lubricants, on the other hand, are rarely used above 400 °F For very high temperatures neither liquids nor conventional solid lubricants are effective, and other lubricating materials are required. NASA scientists have found that metal fluoride salts can be used to provide lubrication at temperatures far above 1, 000 °F. Mixtures of calcium fluoride and barium fluoride, one of the best combinations, perform effectively between roughly 500 °F and 1, 900 °F. Ball bearings using this lubricant have been operated under realistic conditions of

speed and load continuously for over a month at 1,200°F (red heat) and for more than three days at 1,500°F (bright red heat) without failure.

Spectacular results of this kind are representative of one type of NASA contribution in which the outer limits of a technology are explored and the frontiers are established. Such exploratory research, which perhaps is most useful in proving the feasibility of a concept or establishing areas for future research, often does have immediate, although limited, application. Mixtures of fluoride salts have been shown to be very effective as thread lubricants for use in high speed aircraft where temperatures of about 1,200°F are encountered. Similar materials are currently being examined as lubricants for control surface bearings of the shuttle craft; these bearings must operate at temperatures in excess of 1,500°F. In addition, fluoride salts offer the promise of being useful as lubricants in other areas where very high temperatures are encountered, such as in the glass forming industry and in the manufacture of iron and steel.

Improved Bonding Methods for Dry Film Lubricants

Solid lubricants offer a number of potential advantages when compared to oils and greases. Overall design can be greatly simplified if a dry film, rather than a circulating oil system with a pump, heat exchangers, and seals, is used to lubricate a system. In addition, solids generally exhibit better stability and possess better lubricating properties at extreme temperatures and in chemically reactive environments.

Two of the greatest drawbacks to using solid lubricants, however, are short lubricant wear life and the associated problem of the reliability of a bearing lubricated in this fashion. Most of the patents that have been issued in the area of dry film lubrication are concerned with ways of providing increased wear life for the lubricating film. A fairly successful solution to the problem has been the use of various types of binders. These materials bond the lubricant to the substrate surface as well as provide a tough finish that is worn down very slowly during the operation of the bearing. NASA has been responsible for much of the research that has resulted in greatly improved dry film binders. The use of ceramics, inorganic phosphate and silicate salts, and more recently, thermally stable resins, as lubricant binders was initiated and further developed by NASA scientists and contractors.

Binders have certain deficiencies, however. Ceramics and inorganic salts normally require a separate fusing step that may demand a stringent control of time and temperature, and may be at such an elevated temperature that thermal damage to the bearing alloy could result. Ceramics must have a coefficient of expansion similar to the bearing material to avoid crazing. Organic resins must be thermally cured to develop optimum properties. Many of these disadvantages have been eliminated through a technique developed by NASA scientists that employs sputtering as a way of applying dry film lubricants to a surface. Pure lubricants are used, and no binders are necessary. The films that are formed are highly uniform and adhere very tightly to the surfaces of bearings. As a result, only very thin layers of lubricant are required for good wear life. It is this latter feature of sputtered films that users are finding so attractive. Bearings machined to extremely close tolerances and operating with very little clearance between the moving parts can be reliably lubricated for periods of time far longer than those obtained using burnished films.

NASA personnel have also developed ion plating as a means of applying a thin film of a lubricating metal, such as gold, to a bearing surface. In this case, also, very uniform, tightly bonded films are formed which have consistently longer wear lives than films formed by other processes, such as electroplating.

Taken as a whole, these developments represent a significant advance in the state-of-the-art of lubrication. Dry films are not about to replace oils and greases as the lubricant for most commercial applications today, or even in the foreseeable future. Yet in large measure, because of NASA's contributions, solid lubricants can now be counted on to provide reliable lubrication under conditions where liquids are no longer suitable, such as at very high or very low temperatures, under extreme loads, in high vacuums or in reactive environments.

Evaluation of High Temperature Lubricant Fluids

A significant dimension of NASA contributions to the whole field involves the evaluation and testing of lubricants, bearings and bearing materials. Testing and evaluation are essential, for they not only permit the selection of an optimum material or configuration for any given set of conditions, but provide information on parameters such as lubricant viscosity and bearing life expectancy that are required by the engineer to actually utilize these materials in an operational capacity.

A typical example of this type of contribution is the tests NASA conducted to determine the most effective lubricant fluids for use at 600°F. On the basis of an initial screening program, three candidate fluids were selected for further testing. Subsequent tests revealed that a synthetic paraffinic oil containing an antiwear additive and an antifoaming agent provided the most effective lubrication at 600°F in a low oxygen environment. The end result of these studies has been more than the selection of a new high temperature lubricant. A body of knowledge was made available that has permitted the design engineer to include 600°F hydrodynamic bearings in designing future high temperature machinery and equipment. He knows what metals to use for a given lubricant fluid and the approximate bearing life to be expected under a given load at given temperatures. NASA contributions of this sort have played an essential role in facilitating the development of improved equipment utilizing new materials, concepts and designs.

Conclusion

This review of three examples of NASA contributions to the technology of the lubrication field serves to illustrate the fundamental nature of space program research. The review demonstrates that within the range of contributions, some advances are forward looking in anticipation of new requirements and some are primarily a consolidation of the technology in maximizing present capabilities. Section III and its Attachment describe the formal and informal communication mechanisms used by NASA and its personnel to facilitiate the transfer of its technical contributions.

SECTION III. COMMUNICATIONS OF NASA CONTRIBUTIONS

The results of NASA research and development work in the lubrication field have been disseminated to persons outside the space program through (a) contract activities, (b) various publications, and (c) regional technical information centers. In addition to these more formal communication activities, NASA in-house and contractor personnel stimulate technology transfer through such professional activities as presenting papers at society meetings and participating in the establishment of lubrication standards.

This section focuses on the more formal ways NASA has announced the results of its research in lubrication. The major reason for this emphasis is that the most complete transfer data available concern the more formal communication activities. A brief description of relevant informal communication activities is presented in Attachment III.

Contract Activities

Technology transfer is fostered through a number of direct and indirect mechanisms. One of the more important transfer procedures involves the commercial utilization of technical know-how NASA contractors develop during the course of their work for the space agency. In the case of lubrication technology, certain examples can and will be cited which demonstrate the nature of the transfer process. Before examining specific examples, however, the general pattern associated with such transfer activities should be considered.

- An in-house NASA research group working on a particular problem discovers a technically feasible solution.

- Having demonstrated technical feasibility, NASA prepares and distributes a work statement (a "request for proposal" or RFP) to organizations which may be able and interested in continuing development work on the proposed solution. An RFP sometimes serves the important communication function of announcing to qualified parties the nature of specific innovations which have occurred in NASA laboratories.

- One or more organizations respond to the RFP.

- One or more responding organizations are selected to continue the development work. Contracts are negotiated and additional research is performed. During the course of such development work, contracting firms evolve capabilities in terms of personnel and equipment which allow them to satisfy, at a minimum, NASA mission requirements. In addition, contracting firms with commercial interests extending beyond NASA requirements, may discover one or more ways in which the technical competence gained on the NASA contract can be used in other areas of their industrial operations.

Three examples involving NASA-sponsored research in the lubrication field will illustrate the technology transfer function which contracts can serve. The cases cited do not emphasize the details of the specific technologies; such information is available in the Transfer Example File Summary reports presented in Attachment IV.

Under a contract (NAS 8-1540) to the Marshall Space Flight Center, the Midwest Research Institute (MRI) developed a number of dry solid film lubricants for use in the space program. One of the lubricants incorporated a polyimide resin binder which permitted exceptional wear life characteristics over a wide range of operating temperatures.
Vern Hopkins, MRI's assistant director of engineering, said his firm applied for a patent waiver from NASA because the commercial potential of the new lubricant appeared quite good. After obtaining a patent waiver in May 1967, MRI licensed National Process Industries to manufacture and market the new lubricant. National Process Industries, a small solid film lubricant firm in South Gate, California, reports the sales volume of the lubricant is approximately $1,000 per month. (See "Polyimide Resin Solid Film Lubricant" Transfer Example File Summary in Attachment IV.)

SKF Industries, Incorporated in King of Prussia, Pennsylvania has held several NASA contracts in the last ten years. During the course of their contract work, SKF has tested and developed several lubrication concepts originating at the Lewis Research Center. For example, in the mid 1960's SKF undertook a series of tests for Lewis to investigate the performance of eleven high temperature liquid lubricants at extreme environmental conditions representative of advanced turbine machinery. SKF engineers reported the results of those tests in a NASA Contractor Report entitled, "Bearing-Lubricant Endurance Characteristics at High Speeds and High Temperatures" (Wachendorfer and Sibley, 1965). In addition to satisfying NASA mission requirements in such contracts,

SKF vice president Tibor Tallian said his firm has been able to use the expertise gained to improve the lubrication of bearings used in certain aircraft. (See "Fluid Lubricated Bearing Testing" Transfer Example File Summary in Attachment IV.)

A C Electronics, a division of the General Motors Corporation in Milwaukee, Wisconsin, was awarded a contract (NAS 9-469) by the Manned Spacecraft Center to produce one type of gyroscope to be used in NASA spacecraft. New Departure-Hyatt (NDH), another GM division, received a subcontract from A C Electronics to assist in the project. NDH designed and produced the lubricated ball bearings used on the gyroscope spin axis. During the course of this contract work, NDH engineers developed important knowledge concerning the relationships among (1) surface finish of bearings, (2) behavior of the lubricant fluid, and (3) surface deterioration of bearings. Research supervisor Bryce Ruley recently indicated that NDH has been able to use the technical competence it developed on this subcontract to create a new manufacturing process, the specific nature of which is proprietary. (See "Fluid Lubricated Bearing Testing" Transfer Example File Summary in Attachment IV.)

In all three of the illustrations selected, the main point is that each contracting firm has been able to transfer technologies developed for NASA purposes to other applications extending beyond the original contract. Dialogue between NASA and the contractors served to clarify problem areas requiring new lubrication technology; communications involving NASA, the contractors, and third parties also provided opportunities to extend the applications of the technology beyond the NASA mission for which the work was originally undertaken. The transfer example files in Attachment IV present more elaborate descriptions of the technical work performed and the transfer activities involved in these three cases.

Formal Publications

The space agency has developed an extensive formal publications program which in-house and contractor personnel use to report the results of their research and development work in the lubrication field. Table 3-1 shows the number of titles related to lubrication in each NASA-funded publication category from 1963 through 1969.

To give some feel for the scope of lubrication technology reported in these publications, one approach is to examine the Tech Briefs issued during the past eight years. The contents of Tech Briefs

are, to some extent, representative of the technologies reported in other NASA documents. In fact, Tech Briefs sometimes are used to announce the availability of other NASA publications.

TABLE 3-1. NASA PUBLICATIONS PRESENTING AMERICAN SPACE PROGRAM CONTRIBUTIONS TO THE LUBRICATION FIELD: 1963-1969

YEAR OF PUBLICATION	TYPE OF PUBLICATION						
	Technical Reports	Contractor Reports	Technical Notes	Tech Briefs*	Technical Memorandums	Other Special Publications	TOTALS
1963	13	1	2	4	1	0	21
1964	11	12	5	3	2	0	33
1965	13	14	7	3	2	1	40
1966	12	13	5	7	5	2	44
1967	16	15	6	3	6	0	46
1968	8	8	7	5	15	1	44
1969	6	14	16	13	2	2	53
TOTALS	79	77	48	38	33	6	281

* Tech Brief titles related to lubrication technology,including four issued in 1970, are presented in Attachment III.

From 1963 to 1971, NASA prepared and disseminated 43 Tech Briefs which describe contributions to the lubrication field flowing from the space program. For analytical convenience, the Tech Briefs may be divided into three categories: those describing new or improved lubricants, those presenting new or improved methods for applying lubricants, and those reporting lubricant testing techniques. Table 3-2 indicates that the vast majority (86 percent) of the Tech Briefs announce either new and improved lubricants or novel ways of providing lubrication. The data in Table 3-2 also identify the field centers which produced the Tech Briefs.

TABLE 3-2. TECH BRIEF CATEGORY BY ORIGINATING NASA FIELD CENTER

TECH BRIEF CATEGORY	NASA FIELD CENTER			TOTALS
	Lewis	Marshall	Other	
New or Improved Lubricants	13	3	5	21
Lubricant Application Methods	6	6	4	16
Lubricant Tests	3	2	1	6
TOTALS	22	11	10	43

Roughly one in every two of these Tech Briefs was prepared at the Lewis Research Center. This is not surprising since Lewis is the one NASA field center with a formally organized lubricants branch. The specific nature of the in-house capability at Lewis is reflected partially by the data in Table 3-3.

TABLE 3-3. IN-HOUSE VERSUS CONTRACTOR GENERATION OF LUBRICANT TECHNOLOGY BY FIELD CENTER PRODUCING TECH BRIEF

CENTER PRODUCING TECH BRIEF	TECHNOLOGY ORIGIN		TOTALS
	In-House	Contractor	
Lewis	18	4	22
Marshall	2	9	11
Other	1	9	10
TOTALS	21	22	43

Approximately four-fifths of the Tech Briefs from Lewis announce the results of research conducted by in-house personnel. In sharp contrast, roughly the same proportion (85 percent) of the lubricant Tech Briefs produced by other NASA field centers reported innovations developed by contractor personnel.

The relevance of these Tech Briefs to work outside the space program is attested to, in part, by the interest people have shown in them. During the last three years, for example, they have made 786 specific requests to NASA for the Technical Support Packages (TSP's) associated with the 43 Tech Briefs. Data in Figure 3-1 demonstrate that the number of 1968-1970 TSP requests spans across all three technical categories and parallels closely the number of Tech Briefs and TSP's published in those categories. The specific ways engineers have been able to use these TSP's are examined in Section IV.

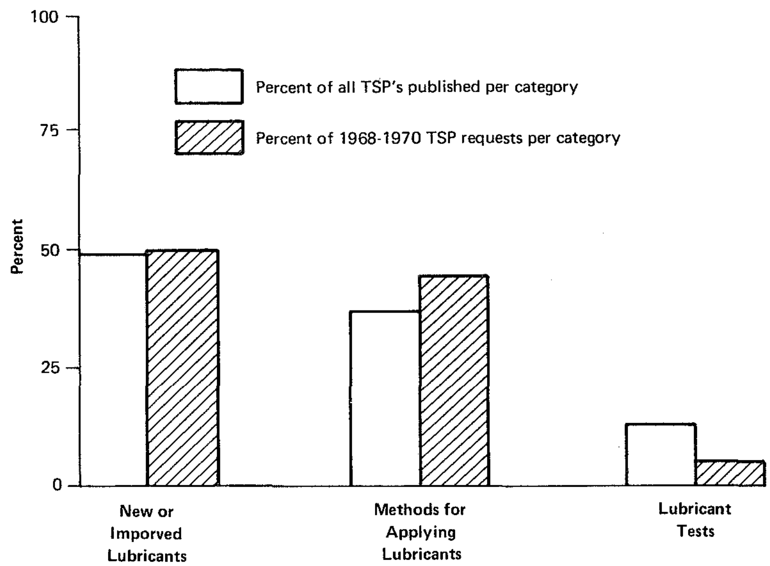

Figure 3-1. 1968-1970 TSP Request Frequency Compared With Total TSP Production for Three Technical Categories.

Regional Dissemination Center Activities

During the past eight years, the Technology Utilization Office of NASA has developed a series of experimental programs designed to accelerate the flow of new technology to potential users. The Tech Brief program described above represents one type of experiment involving the publication and distribution of documents. Another experiment, totally different in kind, involves the operation of Regional Dissemination Centers (RDC's). The RDC program consists of a network of six geographically dispersed computerized information storage and retrieval centers which possess the scientific and technical information base used by NASA scientists and engineers. Qualified RDC personnel search the computer tapes for appropriate aerospace technology in response to specific requests from clients who pay for the service. RDC's provide clients with specialized packages of information applicable to given problems. (A more elaborate description of RDC's and other experimental NASA technology utilization programs is presented in Cantor, 1971, pp. 26-41.)

RDC's have played an important role in making client-firms aware of NASA work in the lubrication field. Each month during 1969 and 1970, for example, the Aerospace Research Applications Center (ARAC) at the University of Indiana has prepared current awareness

literature searches (Standard Interest Profiles) related to lubricants and bearings technology which they have distributed to twelve different client-firms. Another RDC, the North Carolina Science and Technology Research Center (STRC), has been performing special literature searches for clients interested in aerospace-generated lubrication technology since 1965. In a three month period in 1966, for example, STRC personnel reported the completion of NASA data base literature searches related to lubricant migration, lubrication optimization techniques, and lubrication qualities or organic films and coatings. The fact that RDC clients pay for these searches demonstrates the significance of this transfer mechanism.

Conclusion

Establishing meaningful communication links between NASA and potential industrial users of aerospace-generated technology certainly is an essential part of the total technology transfer process. The real value of such links comes into focus when viewed in the context of what happens to the communicated information. Section IV presents a profile of non-NASA application activities associated with space program contributions to the lubrication field.

SECTION IV. A TRANSFER PROFILE

The usefulness of NASA-generated lubrication technology to industrial engineers can be demonstrated to some extent by examining attempts such persons have made to use that technology. To generate sufficient data concerning this type of nonaerospace application activity, several hundred persons who showed interest in NASA-developed lubrication technology were contacted. This section presents the results of that survey.

Three Dimensions of the Technology Transfer Process

Before describing the specific details of the application activities identified in the survey, it will be useful to examine three dimensions of the technology transfer process: the types of lubrication technology involved; the transfer stages that occur; and the action status of application activities. Once these three dimensions are understood, they can be used to place specific examples of technology transfer into a meaningful frame of reference.

Three types of NASA documents that treat lubrication technology can be distinguished: those reporting new or improved lubricants; those describing methods for applying lubricants; and those presenting innovative lubricant test programs. The Tech Brief Exhibit in Attachment III identifies specific kinds of technical innovations associated with these three categories.

Transfer stages may be divided into four categories. Stage 1 transfers involve the recognition of opportunity and searches for additional information to determine the relevance of innovations to professional activities. Stage 2 transfers include laboratory verifications of lubrication theories, designs or application ideas. Transfer cases are classified in Stage 3 when organizations are market testing prototypes or are using new lubrication techniques in their operational activities. Stage 4 transfers include those situations in which adopters are selling new or improved lubricants or lubricant application services developed originally under NASA funding. Organizations active in the first three transfer stages are referred to as adapters; their primary goal is to adapt or transform a technology for new applications. Organizations active in the fourth transfer stage are referred to as adopters; they market new applications of adapted technology.

The action status of transfer activities refers to the dynamic nature of the transfer process at the time contact is made with organizations. For convenience, two action statuses are distinguished: those which are continuing; and those which have terminated. As will be shown, interest in an innovation may progress through all four transfer stages; or it may continue indefinitely in one or another of the transfer stages; or, finally, interest may terminate in any of the transfer stages. Cases are classified as terminated when (a) no further adaptation or adoption activities are contemplated, (b) a better technical alternative has been found, and/or (c) continued transfer activity is not economically feasible.

The Survey

Technology transfer processes are triggered and facilitated by several different types of communication activities. As explained in Section III, NASA contributions to the lubrication field have been communicated to other organizations through contract activities, formal publications and Regional Dissemination Centers. Attachment III of this presentation also identifies instances in which transfer activities have been stimulated through personal contacts and participation in professional society activities.

To generate data illustrating transfers of NASA-developed lubrication technology, the Tech Brief program was selected for special examination. During the past three years, a substantial body of transfer activities associated with this program has been developed which make it possible to draw some general conclusions about the nature of the transfer process. Emphasis on transfer efforts related to Tech Briefs is particularly appropriate for one additional reason: to a large extent, the technical contents of Tech Briefs mirror the specific innovations that occur during the conduct of NASA-funded research and development work.

As noted in Section III, 43 Tech Briefs have been published since 1963 in which new lubrication technology has been reported. With reference to the types of lubrication technology presented in those Tech Briefs, 21 describe new or improved lubricants, 16 deal with methods for applying lubricants or providing lubrication, and 6 report the development of lubricant testing techniques or novel evaluation testing procedures. Persons outside the space program have made 786 specific requests to NASA for Technical Support Packages (TSP's) associated with the 43 Tech Briefs.

A survey was conducted to generate illustrations of the way technical ideas described in the 43 TSP's have transferred to nonaerospace uses in the United States. Mail questionnaires were sent to 240 of the TSP requesters approximately six months after they had requested the documents. The six month time delay was considered sufficient to enable TSP requesters to make at least initial decisions concerning their uses of the documents. One hundred forty-one (59 percent) of the requesters contacted responded. Their responses were divided into four groups according to the stage of transfer activities involved. Subsequently, telephone interviews were conducted with persons who had indicated on their questionnaire that they were engaged in either Stage 3 or Stage 4 transfer activities.

Survey Results

A profile of the different stages of transfer activities identified in the survey is presented in Figure 4-1.

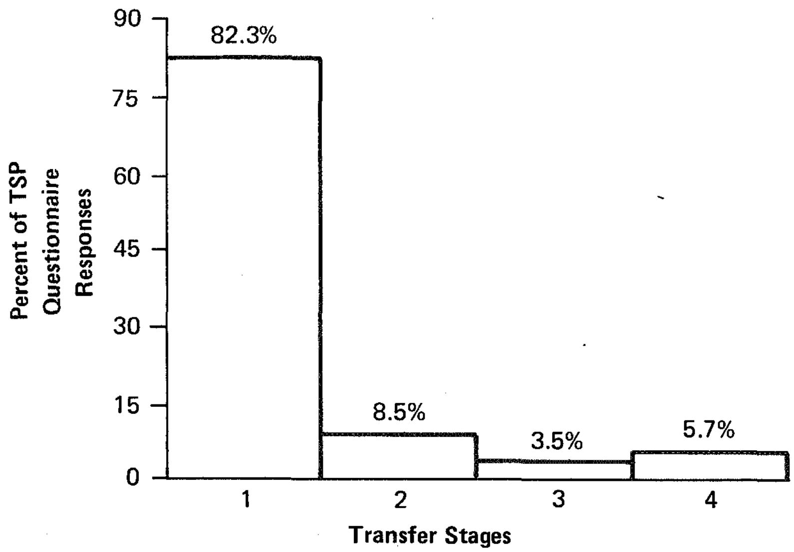

Figure 4-1. Transfer Profile of 141 Persons Using TSP's Related to Lubrication.

Approximately four-fifths (82.3 percent) of the 141 respondents indicated they either had used the TSP's to keep up to date with new developments in the lubrication field, or were still trying to determine the relevance of the technology to their organizational needs. For

example, the J. H. Day Company in Cincinnati, Ohio ordered TSP 68-10261 describing a dynamic reservoir lubricating device. The company manufactures industrial food and chemical mixers, including a unit that operates at speeds up to 10,000 rpm. The product engineer who examined the TSP concluded that the NASA lubricating device would provide an excellent design improvement if and when the present design proves inadequate. He indicated the TSP also should be useful as attempts are made to develop new machinery. (See "Dynamic Reservoir Lubricating Device" Transfer Example File Summary in Attachment IV.)

Another Stage 1 transfer example may be cited to demonstrate that benefits are sometimes established in this stage and require no further adaptation activity. The Anchor Hocking Glass Corporation in Lancaster, Ohio evaluated TSP 68-10340 describing a method of sputtering solid lubricants onto different surfaces. Company engineers said that by studying the TSP they were able to determine that the sputtering method was not satisfactory for their needs. One of the engineers indicated the information provided in the TSP showed clearly that additional research the firm had planned was unnecessary. The Anchor Hocking experience is an illustration of how some transfer activities are stage-limited. (See "Sputter Bonding of Solid Film Lubricants" Transfer Example File Summary in Attachment IV.)

Twelve (8.5 percent) of the respondents stated they were laboratory testing lubricants or lubricating methods described in TSP's. An example of the cases grouped in this second stage of transfer activities involves a Hackensack, New Jersey firm using the graphite fluoride described in TSP 69-10250. The firm, Halo Carbon Products Corporation, is conducting an experimental development program that may yield a new lubricant for its product line. (See "Graphite Fluoride" Transfer Example File Summary in Attachment IV.)

The transfer experience of Scot, Incorporated in Downer Grove, Illinois may be cited to illustrate the kinds of factors that can interrupt the adaptation phase of technology transfer. Scot, an electronic component manufacturer, was experimenting with a configuration of lubricated slip rings described in TSP 67-10210. After prototype testing with a variety of lubricants, Scot engineers were able to determine that the performance of a direction finder made by the firm could be improved considerably. At the time of the interview, it was learned that application activities had been suspended in Stage 2. Company officials decided that the proposed improvement would require too

much of an increase in the retail price of the units. (See "Improved Lubrication of Miniature Slip Rings" Transfer Example File Summary in Attachment IV.)

Five of the 141 TSP questionnaire respondents indicated they were market testing prototypes of lubricants or lubricating methods, or that they had incorporated the technology into their manufacturing procedures. One example of such Stage 3 transfer activity involves the National Standard Company in Niles, Michigan. In the early 1960's, National Standard developed a high pressure process for coating wire and proceeded to produce the coated wire commercially. Company engineers experienced difficulty in the manufacturing process which required that the wire be pulled through a steel die. The wire galled and broke in the die as a result of poor lubrication. Several methods of lubricating the die were tried, including the use of ceramic bonded lead monoxide described in Tech Brief 64-10116. The firm began using NASA techniques in its manufacture of the coated wire in 1966 since that technique was the only satisfactory one tested. The National Standard experience in this case is Stage 3 limited since the company will never sell the NASA-developed lubricant commercially. (See "Ceramic Bonded Lead Monoxide" Transfer Example File Summary in Attachment IV.)

Eight persons contacted in the survey stated they have adopted and are marketing NASA-developed lubrication technology reported in TSP's. Two of these Stage 4 transfer cases involve the sputter bonding technology cited above (TSP 68-10340). Varian Vacuum in Palo Alto, California uses the sputtering technique for applying dry film lubricants to components in its own products and offers facilities to perform this service for customers. In addition, the Hohman Plating and Manufacturing Company in Dayton, Ohio sputters dry film lubricants for customers. (See "Sputter Bonding of Solid Film Lubricants" Transfer Example File Summary in Attachment IV.)

Two other cases of Stage 4 transfer activities may be cited to illustrate the fact that organizations are able to use lubricants developed originally for the space program. Both the Marlin Rockwell Division of TRW, Incorporated and the Hohman Plating and Manufacturing Company are marketing ceramic bonded calcium fluoride (TSP 66-10087). Marlin Rockwell, located in Jamestown, New York, uses the technology primarily in lubricating rolling contact and sliding bearings used in high temperature environments (e.g., aircraft engines

and conveyer belts in ovens). Hohman uses the lubricant in similar ways. (See "Ceramic Bonded Calcium Fluoride" Transfer Example File Summary in Attachment IV.)

Conclusion

Nine examples of technology transfer have been cited to illustrate the wide range of activities in which persons using TSP's are applying NASA-developed lubrication technology to solve certain technical problems. More elaborate descriptions of the technology transfer activities involved in these and 15 other cases, including six not related to the Tech Brief program, are presented in Attachment IV.

The examples clearly illustrate the relevance of NASA lubrication work to specific nonaerospace technical problems. They also clarify the fact that while some transfer activities proceed through all four stages, others may continue indefinitely or terminate in different stages for technical or economic reasons.

SECTION V. A FOCUS ON ISSUES

This presentation affords an opportunity to explore the ways in which the professional activities of NASA scientists and engineers complement the organized transfer program established by the space agency. Although only one research program at a single NASA field center was examined in depth here, it is clear that such professional activity plays a common role in other NASA centers (see Attachment III). Thus, similar technology transfer activities can be expected throughout the space agency.

This presentation may also improve the understanding of the contract mechanism as a means of stimulating technology transfer. This mechanisms capitalizes on residual effects derived from the performance of advanced research and development by contracting organizations, who are otherwise participating in a field of technology. Those organizations have the advantage of a market perspective, in addition to a refined appreciation of a particular technical development. The three examples reported in Section III clearly demonstrate the manner in which technology can transfer through the contract mechanism.

The systematic documentation and publication efforts by NASA personnel suggest that special audiences exist that can be associated with different types of technical contributions to the lubrication field. It seems useful to distinguish between basic and applied contributions and associate a professional audience specifically with the basic contributions and a general audience (including the professional) with applied contributions. For example, ion plating of solid lubricants would be a basic contribution while the evaluation of high temperature liquid lubricants would be an applied contribution. The importance of this distinction is that it permits the identification of a need for an intermediary or broker in the technology transfer process. Brokers interpret basic advances in such a way that widespread adoption becomes feasible.

To a large extent, the design engineer acts as a technological broker when basic contributions are made to a field like lubrication. The implication is that the designer transforms basic contributions into an applied form consistent with his adoption constraints. The necessity for transformation affects the integrity of the basic technology transferred. Often only an element or a component of the original technology survives the transformation. The transfer of an applied contribution makes smaller demands on a broker because of the similarity between the contribution and its application; in such cases, the integrity of the transferred technology usually is greater.

ATTACHMENT I

A Brief History of the Lubrication Field

ATTACHMENT I

A BRIEF HISTORY OF THE LUBRICATION FIELD

1839 Patent issued on Babbitt metals.

1853 Patent issued for greases made from soap and crude petroleum.

1859 Drilling of first oil well in U.S.

1880 Continuous distillation process for petroleum put into production.

1884 Reynolds began investigations on fluid film lubrication.

1890 First major use of ball bearings--in bicycles.

1897 Kingsbury constructed a gas lubricated journal bearing.

1914 First national distribution of branded automotive oils by Tidewater Oil Company.

1918 Patent obtained on oleic acid as an antiwear agent.

1925 Antioxidants began to be added to motor oils.

1931 Kingsbury devised an electrical analogy for evaluating incompressible fluid film hydrodynamic pressure distribution.

1938 Mt. Palomar 200" telescope mounted on incompressible fluid hydrostatic bearings. Then heaviest object to be supported in this fashion.

1938 Polybuylene and polymethacrylic acids patented as viscosity index improvers.

1940 Antiwear agents such as tricresyl phosphate developed.

1942 Ethylene-propylene oxide copolymer oils made available.

1943 Silicone oils became commercially available.

1944 MoS_2 examined as lubricant for industrial applications.

1944 Development of dibasic acid esters as synthetic lubricants.

1945 Gatscombe published paper on influence of viscosity-pressure characteristics of lubricant on film formation.

1946 Phosphate esters developed as synthetic lubricants.

1946 First organic binder (carbonized corn syrup) for MoS_2 developed.

1947 Teflon used in lubrication applications.

1947 MoS_2 greases developed.

1948 Halocarbons introduced as less flammable hydraulic fluids.

1948 Alpha Molykote Corporation formed; first commercial source of lubricants containing MoS_2.

1950 Bowden and Tabor published fundamental book on friction.

1952 First military specification, M/L-7866, for MoS_2 solid lubricant.

1955 Eldredge and Tabor explained rolling resistance in rolling element bearings on basis of elastic hysteresis.

1955 International congress on use of MoS_2 as a lubricant.

1955 First application of computers to the analysis of fluid film lubrication.

1957 Polyphenylethers utilized as high temperature, radiation resistant liquid lubricants.

1957 Ceramic binders for solid lubricants developed.

1959 First international symposium on gas lubricated bearings.

1959 Silane fluids first tested as lubricants.

1960 Fluorinated oils available.

1961 Inorganic salts employed as binders to provide dry film lubrication under very high loads.

1962 CaF_2 with ceramic binders shown to be lubricants at temperatures between 500°F and 1,900°F.

1963 Crook concluded that rolling friction under elastohydrodynamic conditions is independent of the load and proportional to film thickness.

1964 Ceramic bonded MoS_2 commercially available.

1964 MoS_2 refractory metal composites prepared by powder metallurgy techniques.

1964 Polyimides used as solid lubricant binders; first organic binder useful at 600°F and higher.

1965 Metals having hexagonal crystal structure shown to have relatively low coefficients of friction.

1965 All major U.S. Automotive manufacturers specified MoS_2 greases for use in suspensions and other parts.

1965 High temperature fluorinated greases commercially available.

1966 Rolamite bearing invented.

1967 Solid lubricant films applied by sputtering.

1967 Fatigue life of ball bearings shown to be dependent on hardness differences between the balls and the races.

1967 Mixtures of CaF_2 and BaF_2 shown to provide effective lubrication for ball bearings operating at 1,500°F.

1969 Metal lubricating film applied by ion plating.

1969 Graphite fluoride developed as a new solid lubricant.

1970 Pyrrones used as high temperature dry film binders.

ATTACHMENT II

Selected Technological Developments to the Lubrication Field That Have Resulted from NASA-Sponsored Research

ATTACHMENT II

SELECTED TECHNOLOGICAL DEVELOPMENTS RELATING TO THE LUBRICATION FIELD THAT HAVE RESULTED FROM NASA-SPONSORED RESEARCH

This attachment to Section II has been prepared in order to examine the three NASA developments reported in that section in greater detail. Further, certain related developments are reported to clarify the significance of those NASA contributions to the field. A more complete listing of NASA contributions is presented in the Tech Brief Exhibit in Attachment III.

Developments in the Area of Dry Film Lubrication

The problem of lubricating bearings operating under severe conditions, such as at extreme temperatures, in high vacuums, or in reactive environments, has in many cases been solved successfully through the use of solid or dry film lubricants. NASA has played such an integral part in the development of the field of dry film lubrication that its contributions are worth examining in considerable detail. Solid lubricants are exactly what the term implies -- solids that possess lubricating properties and so can be used to reduce friction between moving parts. Graphite and molybdenum disulfide are two commonly used solid lubricants. The lubricating properties of these materials arise from their crystal structure; atoms are arranged in sheets which readily slide over one another. The plastic Teflon is another example of a solid lubricant. In this case, lubrication is probably due to the chemical as well as the physical properties of the material. With Teflon there is no tendency to form any sort of chemical bonding interaction with neighboring surfaces, permitting them to move or slide more readily.

Dry film lubrication is not a new technology; pioneers crossing the Rockies in the 1800's lubricated the wheels of their Conestoga wagons with molybdenum disulfide (MoS_2) found along the trail. There has always been one critical problem, however, associated with the use of solid lubricants; they quickly wear off. Much of the research in this field has been devoted to finding ways of improving film wear life.

Improved binders. The use of a binder in conjunction with the lubricant is the approach commonly used in the industry today to improve the wear lives of solid lubricants. Binders help bond the lubricant to

the substrate surface as well as provide a tough surface that is worn down very slowly during the operation of the bearing. The first binders, introduced during the 1940's, were organic materials. Although they lacked thermal stability (the maximum service temperature was about 300°F), such lubricant-binder compositions had greatly extended wear lives compared to burnished films. Today a great many different types of binders are used. They include additional types of organic resins as well as ceramic and nonceramic inorganic materials.

NASA-sponsored research has been responsible for the development of a number of these new binder systems. A group at Lewis Research Center, for example, pioneered the use of ceramics as lubricant binders. Although ceramics offer exceptional thermal stability, their coefficient of expansion must closely match that of the metal substrate or crazing and rapid film failure will occur. Through the use of such ceramic materials as silica, cobaltous, and boron oxides, binders have been developed that can be used on a range of metals and alloys. Vitrolube, an excellent solid film lubricant privately developed by North American Rockwell, uses a mixture of MoS_2 and graphite in combination with a proprietary ceramic binder; it is one of the best commercial examples of this concept.

The Midwest Research Institute (MRI), under contract to the Marshall Space Flight Center, formulated the highly regarded MLF series of dry film lubricants which utilize inorganic phosphates and silicates as binder materials. Although these lubricants do not exhibit the wear life of resin bonded films in applications where movement is a prime design consideration, they have a number of very desirable features. Many are useful within a temperature range of about 300°F to 1,000°F. They are not subject to outgassing in a high vacuum and are compatible with liquid oxygen. Most of them can be used in extremely high load situations, for example, with loads in excess of 100,000 psi.

More recently MRI, again under contract to the Marshall Space Flight Center, developed a group of solid film lubricants that use polyimide and pyrrone resins as binder materials. These lubricants have a low coefficient of friction and possess exceptionally good wear life. Of greatest significance, however, is that they can be used for extended periods of time at 600°F. This temperature is nearly 200°F higher than what can be attained using phenolic and epoxy resins, the next best commercially available materials.

Improved application methods. The scope of NASA's contributions in the area of dry film lubricants extends far beyond the development of new binder formulations. Two entirely novel ways of applying a film of solid lubricant to a substrate surface have been developed through NASA's in-house research program. One utilizes sputtering. The other involves the use of ion plating, and in a more recent reginement, ion plating in combination with flash evaporation.

Although it is a fairly old technique, sputtering was first examined and subsequently refined by a research team at Lewis as a way of applying a solid lubricant coating. In the sputtering process the solid lubricant material, for example, a compacted cylinder of MoS_2, is bombarded with argon ions which are present as a plasma. Some of the MoS_2 molecules that are dislodged in this process strike the surface of the material to be plated, where they form a tightly bonded, even coating. The wear life of coatings prepared in this fashion has proved to be exceptionally good. One reason for this appears to be the extremely clean surface to be plated (reverse sputtering) removes any adhering film of oxide or moisture, and exposes a fresh surface of unoxidized metal. Strong covalent bonds between coating and substrate can thus be formed. Another advantage of sputtering is that it permits a very even film layer of any thickness to be deposited. The film thickness required for good wear life is typically less than 1/10 that of a film employing a binder. Although sputtering could be used originally only to provide coatings of conductors (e.g., gold) or semiconductors (e.g., MoS_2), refinements in the technique now allow essentially nonconducting lubricants such as CaF_2 to be deposited as a coating in this manner.

Ion plating also involves the use of a plasma, so that extremely clean substrate surfaces can be obtained. In this plating technique, the lubricant is introduced as a vapor into the argon plasma, where it is immediately converted to positively charged ions. A negative potential is applied to the surface of the material to be plated, causing the lubricant ions to be attracted with considerable force. When a very large negative potential is used, ions collide with the surface at such high velocities that they penetrate into the substructure of the material being plated. An extremely well anchored film is formed. An ingenious method of plating nonconducting materials in this manner has also been devised. A conducting screen is placed directly in front of the substrate. The positive ions are attracted to the screen, but many of them pass through and impinge on the substrate surface. A technique that utilizes ion plating with a screen in combination with flash evaporation has recently been developed by the Lewis group, and patent applications have been filed.

These two techniques for depositing a lubricant film are sufficiently novel that they are just beginning to have an impact on the industry. Varian Associates, perhaps because they already have considerable expertise in sputtering, is now lubricating vacuum components by this process. The Hohman Plating and Manufacturing Company, upon the recommendation of a Lewis engineer, is initiating the use of ion plating to meet the requirements of certain of its customers. (See "Sputter Bonding of Solid Film Lubricants" Transfer Example File Summary in Attachment IV.) Both sputtering and ion plating represent such significant contributions to the state-of-the-art that they undoubtedly will be used for an increasingly large number of applications during the coming decade.

Most of the problems arising from the use of binders have been eliminated during the past decade. These problems include thermal instability in the case of organic materials; moisture sensitivity in the case of inorganic binders (e.g., sodium silicate); the need to match the coefficients of expansion of binder and substrates if a ceramic binder is used; and the fact that many binders have poor lubricating qualities that tend to reduce the effectiveness of the lubricant used. A second distinct advantage of films applied by either sputtering or ion plating is the necessity for only a very thin film in order to provide lubrication for extended periods of time. Films of only 20 millionths of an inch are required, compared to 200 to 1,000 millionths for the typical bonded film. Very close fitting bearings can be lubricated without altering their tolerances. Because they utilize such clean surfaces and afford coatings of such uniform thickness, these techniques also offer a very high degree of reliability. It is likely that all of these parameters--lubrication at high temperature, close tolerances, and a high degree of reliability--will be of increasing importance during the 1970's and 1980's.

Metal fluorides as high temperature lubricants. The discovery of new types of solid lubricants for use at very high temperatures has also resulted from NASA-sponsored research. As early as 1955 it was realized that existing solid lubricants would prove inadequate for the extremely high temperature requirements that would be associated with supersonic flight. A group at Lewis embarked on a program aimed at developing solid lubricants that could function at temperatures up to 2,000°F. Initial work led to the development of a lead monoxide-ceramic binder system that is commercially available in industry today. It is useful between about 500°F and 1,290F. Subsequently, other lubricants have been developed. Among the most promising are

mixtures of calcium and barium fluorides. They have been used in combination with ceramic binders to provide good lubrication up to 1,900°F.

Another way of using these fluoride salts to provide lubrication for a roller bearing device has recently been reported. The cage of a ball bearing assembly was fabricated from a sintered metal. Dry lubricant equal to the free volume of the porous cage was then packed around it. When heated to 2,000°F under an inert or reducing atmosphere, the molten mixture, which has excellent wetting properties, was completely absorbed into the cage. This composite can provide a continuous source of lubricant during the operation of the bearing. Preliminary results using bearings lubricated with these fluoride salts have been very promising. Thrust bearings (20mm bore) have been operated without failure at 5,000 revolutions per minute under a load of 30 pounds for over a month at 1,200°F, and 70 hours at 1,500°F. These fluoride lubricants have one drawback, in that they do not perform well below 500°F. Nevertheless, their ability to permit bearings to operate in a functional capacity at 1,500°F (the entire assembly glows a bright cherry red) is quite remarkable, particularly when placed in the perspective of the maximum operating temperatures of other types of lubricants. Present day commercial aircraft are so designed that lubricants for rolling element bearings are not raised to temperatures above 375°F. For the Boeing Supersonic Transport, this limit has been increased to about 425°F. It is projected that by 1995 new aircraft will require lubricating fluids that can function at 600°F. The best high temperature dry film lubricants in use today provide reliable lubrication up to 700°F, and can be used for short periods of time at somewhat higher temperatures.

Testing and Evaluation of Lubricants

Testing and evaluation are always a necessary part of any developmental program. In some instances, however, the thrust of a contribution focuses upon the testing rather than synthesis or formulation of new lubricants. The materials are already available, but their evaluation for specific applications has still not been performed. Such evaluation is, of course, essential. It permits the selection of an optimum lubricant for any given situation. In addition, it provides information on lubricant stability, bearing wear and fatigue life, and other parameters necessary for the engineer to acutally utilize these materials in a functioning piece of machinery. NASA, through in-house and contract work, has made a large number of important contributions that fall into this testing and evaluation category. Two examples are given below.

Evaluation of graphite fluoride. A definitive study by NASA personnel showed that graphite fluoride, a material first synthesized in 1934, is an excellent solid lubricant. Graphite fluoride, prepared by controlled fluorination of graphite, is a white solid with an empirical formula that can vary from $CF_{1.0}$ to $CF_{1.13}$. It has a crystal structure similar to graphite, with the main difference being that the distance between the lamellar planes has been expanded. Unlike graphite, however, it has high electrical resistance, and can be used in applications where a nonconducting lubricant is required. It appears to be markedly superior to either MoS_2 or graphite as a burnished film, affording up to six times the wear life of the other two materials. Furthermore, it is an effective lubricant for alloys that are not well lubricated with either graphite or MoS_2, as can be seen in Table II-1.

TABLE II-1. COMPARISON OF FRICTION COEFFICIENT AND WEAR LIFE OF BURNISHED FILMS OF GRAPHITE FLUORIDE, GRAPHITE, AND MOLYBDENUM DISULFIDE IN THREE DIFFERENT ATMOSPHERES AT 25°C**

[Moisture content: moist air, 10,000 ppm; dry air, 20 ppm; dry argon, 20 ppm; linear sliding speed, 1.6 m/sec; load, 500 g; riders, 440-C stainless steel.]

Powder	Disk substrate (stainless steel)	Minimum friction coefficient			Wear life, min		
		Atmosphere					
		Moist air	Dry air	Dry argon	Moist air	Dry air	Dry argon
$(CF_{1.12})_n$	301	0.05	0.02	0.025	700	250	50
Graphite	301	.09	Immediate failure[a]	Immediate failure	350	0	0
MoS_2	301	*	Immediate failure	Immediate failure	-----	0	0
$(CF_{1.12})_n$	440-C	.06	.15	-----	1200	450	--
MoS_2	440-C	.15	.02	-----	30	70	--

a Criterion for failure was a frictional force equal to that of unlubricated metal combination.

* Since MoS_2 does not work as well in moist air as it does in either dry air or dry argon, no tests were run in moist air.

** NASA Tech Brief 69-10250.

Graphite fluoride exhibits good thermal and oxidative stability, providing lubrication up to about 750°F. It has a much higher load bearing capacity than Teflon, and could be used in situations where a "clean" (nonstaining) lubricant would be desirable but Teflon cannot adequately perform. Whether or not this material becomes widely accepted will probably depend on its cost. In theory it can be made much more cheaply than Teflon, but at the present time an inexpensive manufacturing process has not yet been developed.

Selection and evaluation of liquid lubricants for use at 600°F. Ten years ago it was projected that supersonic aircraft of the early 1970's would require rolling element bearings operating at temperatures up to 600°F. A group of NASA scientists undertook the project of evaluating all the fluids that might be used as lubricants at this temperature. A preliminary screening program narrowed the candidates down to three, all of which were then available only on an experimental basis. The three materials were a class of polyphenyl ethers, a synthetic paraffinicoil, and a fluorinated aliphatic polyether. An extensive testing program was then undertaken to evaluate each of these lubricants. A number of interesting observations were made during the course of these studies. It turned out that the synthetic paraffinic oil containing an antiwear additive and an antifoaming agent afforded markedly longer bearing life than either of the other two fluids at 600°F in a low oxygen environment. In fact, the polyphenyl ethers failed to provide effective lubrication under these conditions for even short periods of time. They did perform more satisfactorily in an air environment, although bearing life was not as long as had been predicted. The fluorocarbon fluid, although it possessed excellent thermal stability, caused corrosion of certain alloys at temperatures above 550°F; this also was shown to have other drawbacks. It did not exhibit consistent lubricating characteristics, producing extensive wear in some cases and very low wear in others. Because of its high density and low thermal conductivity, it was not as good a coolant as the other lubricants. Under identical operating conditions, bearings tended to stabilize at a temperature 100°F to 125°F above that observed for the bearings lubricated with the other two materials. None of these results could have been accurately predicted beforehand. Indeed, the paraffinic oil gave bearing lives approximately 14 times greater than what was expected on the basis of predictions developed by the Anti-Friction Bearing Manufacturers' Association.

The important end result of these studies, however, is not that a number of interesting, even surprising, facts about different high temperature lubricants were discovered; rather, it is that a body of

new knowledge has been made available that permits design engineers to use bearings operating at 600°F in the design of future aircraft and machinery. They know what metals to use for a given type of lubricant and what range of bearing lives they can expect under given loads at given temperatures. This type of research -- determining operating parameters under conditions that are often forcing the limits of the state-of-the-art -- has been a significant part of the contributions that have been made under NASA sponsorship. It often is not very glamorous, but it has played and continues to play an essential role in the phenomenal growth occurring in the fields of high speed and high performance aircraft, machinery and equipment.

ATTACHMENT III

Communication Activities and Tech Brief Exhibit

ATTACHMENT III

COMMUNICATION ACTIVITIES AND TECH BRIEF EXHIBIT

While the more formal channels for communicating NASA contributions to the lubrication field have been described in Section III, a much larger picture of transfer activities may be drawn by examining the less formal channels which are used. NASA in-house and contractor personnel have maintained close personal contacts with industrial design engineers. In addition, they have participated in the activities of professional societies concerned with lubrication problems.

This attachment focuses primarily on a variety of situations in which technology generated by or for NASA has been communicated to someone outside of the space agency -- situations for which few data have been collected concerning technology transfer activity. The instances cited are meant only to be illustrative of the communication activities involved. They are not to be interpreted as necessarily representative examples. Nor are the instances cited in any sense exhaustive. How frequently such communication activities occur and what impacts they produce are questions which still are not answered. The simple identification of such instances, however, provides a frame of reference for understanding the considerable range of transfer activities in which NASA personnel have been involved.

The attachment concludes with an exhibit which lists NASA Tech Briefs related to lubrication technology.

Personal Contacts With Design Engineers

Although many scientific disciplines are involved in the conception and demonstration of advanced lubrication systems, design engineers exercise a dominant role in lubricant selection and the configuration of particular applications. Early in September 1970, five engineers working in the Lubrication Branch of the Lewis Research Center were interviewed to determine, among other things, how they have communicated the results of their work to design engineers outside of NASA. Three of the five Lewis engineers indicated they have five or more telephone calls each week and three or more visits each month with design engineers interested in discussing specific technical problems.

One example of NASA-generated technology transferring through personal contacts involved Lewis engineer Donald Buckley. Buckley was contacted recently by Richard Matt, a design engineer with the

Fafnir Bearing Company in New Britain, Connecticut. Matt telephoned Buckley to discuss ways of improving a silver plating technique his firm used to lubricate X-ray machine bearings operating in vacuum environments. During a subsequent meeting with Buckley at the Lewis laboratories, Matt determined that the ion plating technique developed by Buckley and others at Lewis was ideally suited to Fafnir's technical requirements. The Fafnir Bearing Company now uses the technique to provide customers with improved silver plated bearings. (See "Ion Plating of Solid Film Lubricants" Transfer Example File Summary in Attachment IV.)

The difficulties associated with tracing technology transfer through such personal contacts are obvious. Foremost among the difficulties, of course, is that the persons involved ordinarily do not record the specific technical nature of such transactions. It is sufficient, however, to report that the engineers interviewed stated many such contacts have occurred and that the adoption of specific lubricants or lubricating techniques originally developed by NASA is commonplace through this mechanism.

Professional Society Activities

NASA personnel have been able to facilitate transfers of their contributions to the lubrication field by presenting papers before several professional societies. Table III-1 gives some feel for the types of topics presented as well as the variety of professional groups with which Lewis Research Center personnel have been involved. This table is intended simply to illustrate the fact that NASA lubrication engineers have found a number of opportunities in professional meetings to share the results of their research work with other professionals.

TABLE III-1. AN ILLUSTRATIVE LIST OF LUBRICATION PRESENTATIONS DELIVERED BY NASA LEWIS RESEARCH CENTER ENGINEERS

Lewis Speaker	Title	Occasion	Place	Date
Anderson, W.J.	"The Effect of Lubricant Viscosity on the Cooling and Lubrication of Cylindrical Roller Bearings at High Speeds"	Annual Meeting of the American Society of Lubrication Engineers (ASLE)	Cincinnati, Ohio	April 1963
Cunningham, R.E.	"Experimental Stability Studies of the Herring-bone-Grooved Gas Lubricated Journal Bearing"	International Lubrication Symposium	Las Vegas, Nevada	June 1968
Fleming, D.P.	"Zero-Load Stability of Rotating Externally Pressurized Gas-Lubricated Journal Bearings"	Joint Lubrication Conference of the American Society of Mechanical Engineers and the American Society of Lubrication Engineers	Houston, Texas	October 1969
Parker, R.J.	"Effect of Oxygen Concentration on Synthetic Paraffinic and Advanced Ester Base Lubricants in Bearings Tests at 400°F to 450°F"	Spring Lubrication Symposium of the American Society of Mechanical Engineers	San Francisco, California	June 1969

In addition to their speeches before professional groups, NASA personnel have held prominent positions in such engineering groups as the American Society of Mechanical Engineers and the American Society of Lubrication Engineers. Lewis Lubrication Branch Chief Robert L. Johnson, for example, served as ASLE president in 1968; he was also a National Director for ASLE from 1962 to 1967. Johnson participated in many of the twelve technical committees operating within the organization and helped form four of them. The ASLE technical committees frequently have provided Lewis engineers with opportunities to discuss the results of their research and development work with design engineers outside NASA.

This review of NASA participation in professional society activities concludes with a brief reference to the fact that articles describing space program contributions to lubrication technology have appeared in many scientific and technical publications. Table III-2 provides five examples of articles written by Lewis engineers which illustrate the variety of topics and publications used. As with previous illustrations cited earlier in this Attachment, these citations are made to emphasize

the variety of ways in which NASA-generated technology is transferred. Research is required to determine the extent to which design engineers have benefitted from their use of these articles.

TABLE III-2. AN ILLUSTRATIVE LIST OF LUBRICATION ARTICLES AUTHORED BY NASA LEWIS RESEARCH CENTER ENGINEERS

NASA Author(s)	Title	Publication	Date	Pages
Allen, C. W., D.P. Townsend, and E.V. Zaretsky	"Elastohydrodynamic Lubrication of a Spinning Ball in a Nonconforming Groove"	Journal of Lubrication Technology Vol. 92, No. 1	January 1970	89-96
Buckley, D.H., and R. L. Johnson	"The Influence of Crystal Structure and Some Properties of Hexagonal Metals on Friction and Adhesion"	Wear, II	1968	405-419
Fusaro, R. L., and H. E. Sliney	"Preliminary Investigation of Graphite Fluoride (CFx)n As A Solid Film Lubricant"	NASA TN D-5097		
Parker, R.J., E.N. Bamberger, and E.V. Zaretsky	"Evaluation of Lubricants for High-Temperature Ball Bearing Applications"	Transactions of the ASME	January 1968	106-112
Zaretsky, E.V., and W.J. Anderson	"How To Use What We Know About EHD Lubrication"	Machine Design	November 7, 1968	167-173

Tech Brief Exhibit

Several different types of documents that NASA in-house and contractor personnel have used to report the results of their lubrication work were described in Section III. That description of NASA-funded publications emphasized, among other things, that the technologies reported in Tech Briefs may be considered to be broadly representative of the scope of technologies presented in other NASA publications. The following exhibit presents a detailed listing of 43 Tech Briefs related to lubrication. They are divided into three groups: those announcing new or improved lubricants; those dealing with methods for providing or applying lubricants; and those reporting on lubricant testing techniques.

TECH BRIEF EXHIBIT

Technical Category	Tech Brief Number	Tech Brief Title
New or Improved Lubricants	63-10337	Gallium is Useful Bearing Lubricant in High-Vacuum Environment
	63-10453	Molybdenum Disulfide Mixtures Make Effective High-Vacuum Lubricants
	64-10116	Lead Oxide Ceramic Makes Excellent High-Temperature Lubricant
	65-10302	Burnishing Technique Improves Lubrication of Threaded Fasteners
	66-10005	Fluoride Coatings Make Effective Lubricants in Molten Sodium Environment
	66-10087	Solid-Film Lubricant is Effective at High Temperatures in Vacuum
	66-10165	Gallium Alloy Films Investigated for Use as Boundary Lubricants
	66-10256	Dry Film Lubricant is Effective at Extreme Loads
	66-10373	Bearing Alloys with Hexagonal Crystal Structures Provide Improved Friction and Wear Characteristics
	66-10609	Film Coating Permits Low-Force Scribing
	68-10249	High-Temperature Bearing Lubricants
	69-10200	High Temperature Coatings for Gas Bearings
	69-10250	A New Solid Lubricant
	69-10360	Improved Gyro-Flotation (Damping) Fluids
	69-10485	Freon, T-Bl Cutting Fluid
	69-10636	Synthesis of Polyethers of Hexafluorobenzene and Hexafluoropentanediol
	69-10661	Foil Bearing Support for High-Speed Rotor
	70-10175	High Temperature Rare Earth Solid Lubricants
	70-10347	Liquid Cryogenic Lubricant
	70-10573	Filled Polymers for Bearings and Seals Used in Liquid Hydrogen
	70-10576	Low-Temperature Radiation-Resistant Material for Ball-Bearing Retainers

TECH BRIEF EXHIBIT (Continued)

Technical Category	Tech Brief Number	Tech Brief Title
Methods for Applying or Providing Lubrication	63-10123	Elastic Orifice Automatically Regulates Gas Bearings
	63-10479	Improved Molybdenum Disulfide-Silver Motor Brushes Have Extended Life
	64-10141	Pneumatic Power is Transmitted Through Air Bearing
	65-10106	Miniature Bearings Lubricated by Sonic Dispersion Method
	65-10366	Unique Gear Design Provides Self-Lubrication
	66-10069	Run-In With Chemical Additive Protects Gear Surface
	67-10007	Composites of Porous Metal and Solid Lubricants Increase Bearing Life
	67-10210	Environmental Study of Miniature Slip Rings
	68-10134	Shallow Grooves in Journal Improve Air Bearing Performance
	68-10165	Bearings Use Dry Self-Lubricating Cage Materials
	68-10261	Dynamic-Reservoir Lubricating Device
	68-10340	Application of the Solid Lubricant Molybdenum Disulfide by Sputtering
	69-10076	Nozzles for Size Reclassification of Microfog Particles
	69-10199	Tools Made of Ice Facilitate Forming of Soft, Sticky Materials
	69-10408	Self-Lubricating Gear
	69-10699	Pulsed High-Voltage DC RF Sputtering
Lubricant Tests	64-10042	Ohmmeter Senses Depletion of Lubricant in Journal Bearings
	67-10379	Machine Tests Slow-Speed Sliding Friction in High Vacuum
	69-10025	Evaluation of Lubricants for Ball Bearings at High Temperatures
	69-10252	Study of High Temperature Bearing Materials

TECH BRIEF EXHIBIT (Concluded)

Technical Category	Tech Brief Number	Tech Brief Title
	69-10367	Study of High-Speed Angular-Contact Ball Bearings Under Dynamic Load
	70-10467	Friction Characteristics of Graphite and Graphite-Metal Combinations at Various Temperatures

ATTACHMENT IV

Summary of Technology Transfer Reports Involving NASA-Generated Lubrication Technology

ATTACHMENT IV

SUMMARY OF TECHNOLOGY TRANSFER REPORTS INVOLVING NASA-GENERATED LUBRICATION TECHNOLOGY

NASA CONTRIBUTIONS	TRANSFER STAGES 1		2		3		4	
	Cont. *	Term.	Cont.	Term.	Cont.	Term.	Cont.	Term.
NEW OR IMPROVED LUBRICANTS								
• Ceramic Bonded Calcium Fluoride		2851**					44299 44300	
• Ceramic Bonded Lead Monoxide					44293		44297 44298	
• Graphite Fluoride			44078				44077	
• Polyimide Resin Binder For Solid Film Lubricants							43633	
METHODS FOR APPLYING OR PROVIDING LUBRICATION								
• Dynamic Reservoir Lubricating Device	44074		22290					
• Hexagonal Crystal Alloy Provides Improved Lubrication			44075					
• Improved Lubrication of Miniature Slip Rings				9025				
• Ion Plating of Solid Film Lubricants					44290		44289	
• Porous Metal/Solid Lubricant Composites			44291	19765			37424	
• Sputter Bonding of Solid Film Lubricants		23994					44295 44296	
LUBRICANT TEST								
• Fluid Lubricated Bearing Testing					44284 44285		44287	

* The action status, continuing or terminated, of transfer cases at the time DRI-PATT contacted users. Cases are classed as terminated when (a) no further adaptation or adoption is contemplated, (b) a better technical alternative has been found, or (c) continued transfer activity is not economically feasible.

** Numbers in columns refer to PATT case numbers.

CERAMIC BONDED CALCIUM FLUORIDE
TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Load-bearing surfaces in space vehicles require special lubrication systems, of which solid-film lubricants provide unique characteristics. In nonspace uses a solid-film lubricant is often advantageous because (1) it can be operated at temperature extremes beyond the capabilities of oil or grease lubrication systems; (2) it does not require cooling, recirculating oil systems with their associated pumps and heat exchangers; and (3) it allows shorter rotating shafts because dry-lubricated surfaces can be located closer to heat sources.

As a result of basic research performed at Lewis Research Center, Harold Sliney developed a mixture of calcium fluoride (CaF2) and a compatible inorganic binder, which is mixed with water to form a slurry and sprayed or brushed on the surface to be lubricated. The coating may vary from 0.0008 to 0.0035 inch. After firing, the lubricating particles are fused to each other and bond the film to the base material. This lubricant has proven effective on a variety of metals, including nickel-base alloys, at temperatures to 1,900°F, in atmospheres containing oxygen or inert gases at pressures from normal atmospheric to high vacuum. It is unstable in hydrogen and other reducing atmospheres.

Marlin Rockwell Division of TRW, Incorporated in Jamestown, New York (44299) installed equipment to apply the ceramic bonded coating of calcium fluoride in 1963. The transfer mechanism in this case was personal contact by the Marlin Rockwell research and development manager on a trip to Lewis. The company coats some of its bearing products on special order from customers. The company's principle application of the technology has been to rolling contact and sliding bearings for high temperature environments such as aircraft engines and conveyer belts for ovens. A company spokesman reports there has been a steadily increasing number of customers for the calcium fluoride coated bearings since 1963.

The president of Hohman Plating and Manufacturing Company in Dayton, Ohio (44300) first learned of the ceramic bonded calcium fluoride innovation when it was described at a technical society meeting in 1963. The company installed equipment to apply the coating in 1963. The principle application has been to bearings for aircraft engines and

conveyer belts in ovens. Hohman has had an increasing number of customers for the service since 1963. The company is continuing its investigation for new applications of the ceramic coating.

S.F.D. Laboratories, Incorporated in Union, New Jersey (2851) has utilized the ceramic bonded calcium fluoride technology in manufacturing magnetron tubes for radar transmitters. The tubes incorporate a bearing that must operate in a vacuum. When S.F.D. research engineers first learned of the Lewis work with calcium fluoride, they investigated the possibility of installing equipment to apply the lubricant to the bearing. Economic factors, however, caused them to abandon their in-house application effort. Instead, S.F.D. contracted with another company to apply the same lubricant film to the S.F.D. bearings. The contract held by S.F.D. to produce magnetron tubes has since been completed.

Control Numbers

Tech Brief Number: 66-10087
NASA Center: Lewis Research Center
PATT Case Numbers: 2851, 44299, 44300
TEF Number: 130
Date of Latest Information Used: October 1, 1970

CERAMIC BONDED LEAD MONOXIDE
TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Conventional lubricants tend to break down in high temperature applications. A dry lubricant in ceramic form made of 95 percent lead monoxide and 5 percent silicon dioxide was developed and tested at Lewis Research Center. Their method of application produces a smooth coating approximately .001-inch thick.

Lead monoxide and silicon dioxide powders are mixed with water to form a slurry which is sprayed onto a preheated surface to be coated. The water evaporates leaving a weakly adherent coating and the surface is then heated to 1,650°F to develop a fusion bond. Only certain metal substrates were recommended for this coating and operation at high surface temperature (above 1,000°F) is necessary to obtain low friction with most ceramic dry film lubricants including this one. With these restrictions, lead oxide ceramic was demonstrated at Lewis to have excellent wear life characteristics.

National Standard Company in Niles, Michigan (44293) has been using ceramic bonded lead oxide in their production of wire for almost five years. In the early 1960's the company developed a high pressure coating process for wire and wanted to produce this type of coated wire commercially. They experienced difficulty in the manufacturing process which required that the wire be pulled through a hole in tool steel. The wire galled and broke in the hole as a result of poor lubrication. Several methods of lubricating the hole were tried. The only successful method was filling the hole with lead oxide frit, baking the mixture to form a ceramic plug, and drilling through this plug to form a ceramic lined hole in the steel. This method has been used since 1966. Earl Weaver of National Standard Company said they would not be making this particular product had they not learned of the ceramic bonded lead oxide development at Lewis.

Holman Plating and Manufacturing Company in Dayton, Ohio (44298) and Marlin Rockwell Division of TRW, Incorporated in Jamestown, New York (44297) have both had facilities to do ceramic bonding of lead oxide for customers since 1964 when the Tech Brief announcing the process was published. Both companies have developed various uses for the technology and have customers for the service.

Since the conditions which require dry film lubricants are comparatively extreme, there is not a wide market for this service; although, as in the case above, when such lubricants are used their use is crucial.

Control Numbers

Tech Brief Number: 64-10116
NASA Center: Lewis Research Center
PATT Case Numbers: 44293, 44297, 44298
TEF Number: 337
Date of Latest Information Used: September 29, 1970

GRAPHITE FLUORIDE

TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Graphite fluoride is a lamellar compound of carbon formed by a controlled chemical reaction of graphite with gaseous fluorine. The resulting crystal structure is similar to graphite, but the distance between lamellar planes is greater. Several years ago Marco Petronio and his associates at the U.S. Army's Frankford Arsenal began to stimulate thinking about using graphite fluoride as a solid lubricant. Robert Fusaro and Harold Sliney of NASA's Lewis Research Center agreed that the material had promising characteristics and acquired from Rice University, through Frankford Arsenal, some graphite fluoride powder for evaluation. In comparative tests with graphite and molybdenum disulfide, the new compound exhibited a comparable or superior coefficient of friction and a wear life up to six times greater. These results were published in a 1969 Tech Brief.

Ozark-Mahoning Company in Tulsa, Oklahoma (44077), a manufacturer of fluorine compounds, is producing new fluorine-carbon compounds including a polymeric carbon monofluoride, wherein the carbon to fluorine ratio is essentially 1:1. Contacts with Lewis Research Center personnel and a Tech Brief describing Lewis tests of graphite fluoride as a lubricant stimulated the firm's entry into this new area. The firm's expertise in fluorine compound manufacturing had led to its selection by Lewis to provide some sample graphite fluoride, and several inquiries were received by the firm as a result of potential users becoming aware of the material through Lewis or Frankford Arsenal contacts. Following issuance of the 1969 Tech Brief, the volume of inquiries increased significantly and the firm established a small-scale production facility in January 1970. The process and equipment are being developed for the production of different grades of carbon-fluorine compounds in order to meet the needs which are expected to develop.

Halo Carbon Products Corporation in Hackensack, New Jersey (44078) first became aware of the characteristics of graphite fluoride through a Japanese publication reviewed during normal literature review

activities. When the NASA test results were announced in the 1969 Tech Brief, the firm was encouraged to begin a development program that may yield a new lubricating product for its product lines.

Control Numbers

Tech Brief Number: 69-10250
NASA Center: Lewis Research Center
PATT Case Numbers: 44077, 44078
TEF Number: 333
Date of Latest Information Used: September 3, 1970

POLYIMIDE RESIN BINDER FOR SOLID FILM LUBRICANTS

TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Under a NASA contract for the development of bearing lubricants, Midwest Research Institute developed several dry solid film lubricants for use in the space program. One such lubricant, developed under the NASA-funded contract, is a solid film lubricant which uses a polyimide resin binder and has exceptional wear life characteristics over a wide range of operating temperatures. Vern Hopkins, assistant director of engineering at the Midwest Research Institute, reported that under the NASA contract they were concerned with developing lubricants which would meet the Marshall Space Flight Center requirements and have the characteristics required for operating temperature, vacuum, environment and durability. Through the inclusion of the polyimide resin binder, Hopkins said they were able to meet the requirements; because the lubricant does have exceptional wear life characteristics, it was felt that the lubricant could also be used commercially. After obtaining a patent waiver from NASA, the Midwest Research Institute licensed National Process Industries in South Gate, California (43633) to manufacture and market the new lubricant commercially.

National Process Industries has a line of dry film lubricants which are used primarily in the aircraft industry. Although the new lubricant may see a wide range of commercial uses, it is primarily aimed at the aircraft industry. Currently the lubricant is being used on the Boeing 737 and by NASA in space programs. Roy Smith, president of National Process Industries, also stated that the lubricant is being considered for use on the SST; attempts are being made to have the lubricant included in the specifications of other aircraft manufacturers. Although the sales on this new lubricant are only about \$1, 000 per month, Smith expects the volume to be doubled or tripled within two years. To date Smith feels that the company has only managed to break even on the new lubricants' sales since it has spent over \$10, 000 in promoting the new product through direct sales contact with aircraft manufacturers.

Although the lubricant has many advantages, Smith said that its acceptance by the commercial market is somewhat hindered by the polyimide binder which requires the material to be refrigerated. At

the present time, the cost of the lubricant and the need for refrigeration means that the lubricant will be limited to a narrow band of hardware items.

Control Numbers

Tech Brief Number:	None
NASA Center:	Marshall Space Flight Center
PATT Case Number:	43633
TEF Number:	336

Date of Latest Information Used: September 9, 1970

DYNAMIC-RESERVOIR LUBRICATING DEVICES

TECHNOLOGY TRANSFER EXAMPLE SUMMARY

The process of supplying lubrication to ball bearings often results in consumption of power, notably when wick feeds are used to transmit oil from a reservoir to the bearing. The wicks introduce friction which consumes power and wastes oil.

In July 1968 a new lubrication method was announced in a Tech Brief. Two employees of the Bendix Corporation, working on a Marshall Space Flight Center contract, designed a system that utilizes the centrifugal force of the rotating bearing to exert an outlet pressure on oil contained in an adjacent reservoir. This assures a controlled supply of lubricant to the bearing only during bearing operation.

Lipe-Rollway Corporation in Liverpool, New York (22290) built and is testing a prototype system for lubricating a roller bearing used under heavy load. The firm has scheduled extensive testing and comparison with alternative methods. If test results are quite favorable, the concept may be incorporated into new bearing design. The J. H. Day Company in Cincinnati, Ohio (44074) also recently evaluated the TSP. The company makes industrial food and chemical mixers, including a unit that operates at variable rpm, as high as 10,000 rpm. No problems have been experienced with the unit's present lubrication system, but the product engineer who requested and studied the TSP concluded that the NASA device would be an excellent design improvement were the present design to prove inadequate. He also said that the configuration of the reservoir and bearing retainer would provide useful sealing features, apart from the lubrication-system characteristics.

<u>Control Numbers</u>

Tech Brief Number: 68-10261
NASA Center: Marshall Space Flight Center
PATT Case Numbers: 22290, 44074
TEF Number: 319
Date of Latest Information Used: August 27, 1970

HEXAGONAL CRYSTAL ALLOY PROVIDES IMPROVED LUBRICATION

TECHNOLOGY TRANSFER EXAMPLE SUMMARY

The long experience of Lewis Research Center engineers in designing lubricants for space use is yielding new metallurgical compositions for medical applications. In the especially difficult lubrication conditions of space where conventional lubricants evaporate and surface oxide films do not reform when worn away, the loss of lubricant film results in metal-to-metal contact, high friction, repeated surface welding-shear reactions, metal transfer and bearing failure.

A solution devised by Robert L. Johnson and Donald H. Buckley of Lewis is to make bearings from alloys with a hexagonal crystal lattice structure and a tailored crystal lattice ratio. Extensive research indicated the existence of large and consistent differences between the shear forces of cubic and hexagonal crystals. When welding occurs between two metal surfaces and the weld shears, it does so along distinct planes in the crystals. Cubic crystals typically exhibit shear forces up to 100 times greater than those in hexagonal crystals, and hexagonal crystals shear smoothly at the surface without changing the surface geometry. As a result, bearings with hexagonal crystal structures will operate much longer than those with the cubic structures.

Lewis studies indicated that cobalt and titanium, both commonly used, can be alloyed in a manner that (1) stabilizes their hexagonal crystal structure over a greater temperature range and (2) increases their crystal lattice ratio. Cobalt normally transforms from hexagonal to cubic structure at 750°F, but alloy additions of tungsten and molybdenum stabilize the hexagonal structure over a wider temperature range. Similarly, binary alloys of titanium with tin or aluminum provide the desired hexagonal structure, and a higher proportion of tin or aluminum yields higher crystal lattice ratios, greatly reduced friction, and minimized surface failure tendencies.

In the medical field, a cubic crystal cobalt-chromium alloy is used in artificial human hip and elbow joints. Lewis studies using a simulated artificial hip joint suggest that wear in these joints probably begins with adhesive wear (interface welds), followed by corrosive wear (chemical surface reactions), and abrasive wear (rough surface and free particle cutting). Consequently, it is likely that artifical hip joint

performance can be improved and prolonged by using hexagonal crystal structure alloys, with optimized crystal lattice ratios. New alloys formulated at the center have a coefficient of friction about half that of conventional prosthetic alloys, and wear rates only one percent of those obtained with currently used alloys.

An orthopedic surgeon at the University of California at Los Angeles (44075) is cooperating with Lewis in experiments to find optimum materials. Tissue compatibility is always of concern when substances are implanted in living tissue, and the surgeon is testing various materials by implanting them in rabbits. Preliminary results of the long-term study suggest that some of the tested alloys are promising materials with respect to tissue compatibility. There is evidence that increasing the chromium content of the alloys improves tissue compatibility without destroying the hexagonal crystal structure. Other materials being evaluated include polyimide plastics and pyrolitic carbon, both of which also show good potential. A continuing problem in the research is the probability that synovial fluid, the body's natural lubricant, may degrade in a diseased joint, complicating the malfunction and even affecting the operation of an artificial replacement.

Control Numbers

Tech Brief Number: 66-10373 (See also TM X-52745)
NASA Center: Lewis Research Center
PATT Case Number: 44075
TEF Number: 220
Date of Latest Information Used: August 27, 1970

IMPROVED LUBRICATION OF MINIATURE SLIP RINGS

TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Space vehicle inertial guidance systems typically incorporate miniature slip ring assemblies to transmit electrical information across the guidance system axes. Circuit performance, especially in null-seeking circuits, is hampered if excessive electrical noise occurs at the sliding contact. The high vacuum of outer space imposes severe environmental conditions for slip ring performance, which must remain operable even on extended missions. Prior to 1966 it was known that unlubricated systems experience galling and erosion effects that cause high localized temperatures, and that reduced heat transfer characteristics of a high vacuum environment would increase the possibility of localized hot spots at contact points. Heightened wear and electrical noise also result from increased friction and surface damage due to cold welding of microasperities.

To extend knowledge of long-term slip ring performance under high vacuum conditions, J. L. Radnik of IITRI was engaged by NASA to perform a laboratory study. The investigation included assessment of the influence of ring, brush, and insulator materials on electrical noise and mechanical wear. The results of the study were published in a September 1966 report and further publicized in a 1967 Tech Brief. Among the more important findings were that soft metal lubricants such as gallium and indium, deposited by a sublimation process on slip rings, provide a considerable improvement in wear and electrical noise characteristics. Also, slip rings made of niobium diselinide in a silver matrix performed better than standard gold slip rings. The silver matrix provides excellent conductivity, and the niobium diselinide functions as a dry lubricant to give low-friction sliding across the contact points. The lubricant transfers back and forth across the metal surfaces, healing tiny faults that may occur in the lubricant film. A 400 hour slip ring operation was evaluated, indicating that electrical noise from slip rings made with these materials quickly reached a maximum level (about the same as that of new unlubricated rings) but did not increase thereafter, because of the low wear characteristic.

Scot, Inc. in Downer Grove, Illinois (9025), an electronic components manufacturer, used the report to confirm in-house knowledge that lubrication would improve slip ring performance. The firm made plans to introduce lubricated slip rings into its miniature

synchromechanisms for commercial aviation instruments and automatic direction finders. The firm's direction finder uses a null-seeking circuit, which the NASA report cited as being especially susceptible to spurious output from brush and slip ring contact.

After prototype testing with a variety of lubricants, it was decided that although performance was improved, the required increase retail price would be too much. Another method for improving their product was developed.

Control Numbers

Tech Brief Number: 67-10210
NASA Center: Marshall Space Flight Center
PATT Case Number: 9025
TEF Number: 74
Date of Latest Information Used: October 28, 1970

ION PLATING OF SOLID FILM LUBRICANTS

TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Solid film lubricants are used in both conventional and high temperature/high vacuum environments. Their use is often limited by problems of obtaining a uniform, strongly bonded film on the substrate metal. Conventional application methods include binders and burnishing.

Binders generally reduce the lubricating properties of the film and undergo chemical decomposition; in addition, their application methods preclude the use of many substrate metals. Unusual storage conditions for the coated surface are a problem with some binders. Burnished films have poor bonding and nonuniform thickness. Both methods produce relatively thick coatings, which creates an adjustment problem in the dimensions of the metal parts being coated.

Lewis Research Center scientists developed another process, somewhat similar to sputtering, which provides a superior lubricant coating for surfaces. As in the sputtering method, an ionized Argon atmosphere is used. The solid lubricant is introduced as a vapor into this atmosphere and the lubricant molecules become ionized. A negative electrical potential is applied to the surface of the material to be plated, causing the positively charged lubricant ions to be attracted with considerable force. When a very large potential is used, ions collide with the surface at such high velocities that they diffuse into the substructure of the material being plated. An extremely well-bonded film is formed. In order to plate nonconducting materials in this manner, a conducting screen is placed directly in front of the substrate surface. The positive ions are attracted to the charged screen, and many of them pass through to impinge on the substrate surface. The wear life of ion-plated solid lubricant coatings is superior to that of any other method for solid film application.

Hohman Plating and Manufacturing Company in Dayton, Ohio (44289) has installed equipment to do ion plating for their customers. This part of their business is currently small with high potential. They have already applied the technique on such diverse jobs as coating internal monitors to be used for hospital patients and coating electrical equipment to eliminate electrical noise and corrosion. Hohman is active in developing the market for this plating technique by finding new

applications, building prototypes and testing their properties. One example of this effort is their research in plating artificial human joints for transplanting.

Another example involves the Fafnir Bearing Company in New Britain, Connecticut (44290). At the recommendation of Lewis engineer Donald Buckley, Hohman applied the technique to improve the silver plating on Fafnir's bearings, which are used in X-ray equipment under vacuum conditions. Hohman does the ion plating for Fafnir. Fafnir is presently negotiating the price of these coated bearings with their X-ray equipment customers. In addition, Fafnir has had some of their other products ion-plated by Hohman in order to test these prototypes for properties and potential cost benefit to customers.

Control Numbers

Tech Brief Number:	None
NASA Center:	Lewis Research Center
PATT Case Numbers:	44289, 44290
TEF Number:	338

Date of Latest Information Used: October 2, 1970

POROUS METAL/SOLID LUBRICANT COMPOSITES

TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Greases and oils may evaporate or break down under high temperatures or vacuum conditions; in such cases, solid bearing lubricants are superior to liquid lubricants. Most dry lubricants, however, tend to wear through exposing the metallic surfaces, causing loss of lubrication and bearing damage.

NASA Tech Brief 67-10007, published in 1967, described new self-lubricating materials with improved wear life. To produce those materials, NASA engineers sintered alloys to form a porous structure which they impregnated with fluoride salts. A thin film of the resulting solid lubricant is added to the load bearing surfaces. NASA filed for a patent on the system and made available nonexclusive, royalty-free licenses.

The technique of impregnating porous metal substrates with calcium fluoride-barium fluoride was originated at Lewis, and the metal substrate was further developed at Midwest Research Institute. This new method of application of the lubricant gave longer wear life. The Boeing Company (44291) monitored the progress in this technology. After additional development of the metal substrate at Boeing, prototypes were made and successfully tested using metal matrix lubricants, as they are now called, for hot duct seals in the Boeing 727. More uses are being investigated at Boeing and prototypes from this material for other seals and high temperature (1, 200° F) bearing cages are now being tested.

Late in 1968, Clevite Corporation in Cleveland, Ohio (19765), an automotive bearing manufacturer, began working with the NASA information to develop a new bearing design for truck and aircraft turbines. Company officials estimated saving $75, 000 and one year of development time by using the NASA technology. A brief market survey with negative results and further engineering evaluation of the design resulted in abandonment of the intended application late in 1969. The firm is exploring other high temperature turbine applications.

Astro Met Associates, Inc. in Cincinnati, Ohio (37424) was granted a license in September 1969 to use the NASA solid lubricant

technology. Company engineers developed their own production methods. Small orders for prototype and evaluation specimens are being filled. The company advertises the applicability of its self-lubricating composites for a variety of industrial uses, including armament sliding components, bearings and seals in vacuum processing equipment, hot gas blowers and pump impellers.

Control Numbers

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NASA Center:	Lewis Research Center
PATT Case Numbers:	19765, 37424, 44291
TEF Number:	63

Date of Latest Information Used: October 5, 1970

SPUTTER BONDING OF SOLID FILM LUBRICANTS

TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Solid film lubricants are used in both conventional and high temperature/high vacuum environments. Their use is often limited by problems of obtaining a uniform, strongly-bonded film on the substrate metal. Conventional application methods include binders and burnishing.

Binders generally reduce the lubricating properties of the film and undergo chemical decomposition; in addition, their application methods preclude the use of many substrate metals. Unusual storage conditions for the coated surface are a problem with some binders. Burnished films have poor bonding and nonuniform thickness. Both methods produce relatively thick coatings, which creates an adjustment problem in the dimensions of the metal parts being coated.

Two Lewis Research Center scientists adapted the fairly old surface coating technique of sputtering to apply solid lubricants, in particular molybdenum disulfide, to surfaces. The sputtering process is carried out in an Argon atmosphere wherein the Argon molecules have been heated to form Argonions. By using an electric potential drop, these ions are first used to bombard and clean the substrate metal surface. The direction of the electric field is then changed, and the ions now impinge on a compact cylinder of dry lubricant (called the "target") transferring their energy to the lubricant molecules. The effect here is much like that with billiard balls. Most of the energized lubricant molecules tend to move in one direction, and the surface to be coated has been placed in their path. As these molecules strike the surface, their energy causes some penetration into the surface. After a short time a thin, graded layer of lubricant is deposited on the surface. The layer is quite uniform in thickness and has a strong, covalent bonding to the substrate metal. The wear life of coatings prepared in this fashion has proved to be exceptionally good.

Varian Vacuum in Palo Alto, California (44296) now uses the sputtering technique for applying dry film lubricant coatings to components in their own products and offers their facilities to perform this service for customers. Varian had contracted with another company to apply dry film lubricants by an expensive, nonsputtering method. The method used did not produce satisfactory results. The Varian sales manager

visited Lewis to investigate developments in coating techniques for high vacuum use and learned of the Lewis innovation in sputtering of dry film lubricants. Varian equipment was slightly modified to do sputter coating in-house and the company both improved the coating on their components and greatly reduced the cost of application. They have a growing number of customers for their coating service and are active in promoting the advantages discovered at Lewis of the technique. Varian is trying to find additional uses of dry film lubrication which might be improved by sputtering.

Hohman Plating and Manufacturing Company in Dayton, Ohio (44295) has installed equipment to perform sputter coating of dry film lubricants for customers. The company president said he first learned of the new coating method when he attended a technical society meeting at which the NASA innovators described the sputtering of lubricants. Hohman offers all of the dry film lubricant coating methods developed at Lewis and is active in finding more uses for all of them.

Anchor Hocking Glass Corporation in Lancaster, Ohio (23994) evaluated the TSP as part of a broad study of methods to improve efficiency and protection of cast iron molds used in glass-making. The sputtering method was deemed inapplicable to the firm's operations because an average of forty mold changes per day necessitates use of a more simple method to apply protective coatings to the molds. However, the TSP confirmed the validity of the firm's judgments about areas needing investigation, and the information made additional research the firm had planned unnecessary.

Control Numbers

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NASA Center: Lewis Research Center
PATT Case Numbers: 23994, 44295, 44296
TEF Number: 293
Date of Latest Information Used: October 2, 1970

FLUID LUBRICATED BEARING TESTING
TECHNOLOGY TRANSFER EXAMPLE SUMMARY

NASA has conducted extensive programs for testing fluid lubricants and lubrication used in ball bearings. Information generated by the analysis of tests has benefited both lubricant producers and bearing manufacturers. The examples given below relate to two different NASA programs: improving bearing wear life under high speed/high temperature operating conditions and stabilizing instrument bearings.

The first program is conducted through the Lewis Research Center to provide lubrication and bearing technology which is required for the continuing development of gas turbine engines. A conventional measurement of bearing operation is the parameter DN, which is the product of shaft diameter (in mm) and shaft speed (in rpm). First generation gas turbine engines operated with mainshaft DN values near one million and temperatures up to 300°F. Current production models operate at DN values to 1.7 million (to 400°F), and development prototypes operate in the 1.8 to 2.5 million DN range (450°F). Engines now in the conceptual stage will require bearing speeds as high as 3 million DN and temperatures above 500°F.

One parameter of the program at Lewis has been the evaluation of fluid lubricants for use in severe operating conditions. In the past, the thermal capacity of lubricating fluids has limited ball bearing design and operation. Lewis scientists conducted an investigation of alternative lubricants for comparison with synthetic diesters, which have been the standard lubricants for gas turbine ball bearings since the early 1950's. Several new synthetic fluids were selected as potential lubricants on the basis of preliminary testing. The fluids were then tested extensively under high temperature operating conditions at SKF Industries, Incorporated in King of Prussia, Pennsylvania (44285), under contract to Lewis. The tests consisted of running similar ball bearings lubricated by the different fluids with similar conditions of speed, load and high temperature. SKF scientists reported the results of these tests in NASA CR-74097. The test results also appeared in NASA TN D-4146 and in a technical paper published in Transactions of the ASME.

A company spokesman reported recently that SKF researchers have derived from the tests several findings regarding lubricant/bearing

surface interaction. The findings have been used in specifying more resistant high temperature fluid lubricated bearing surfaces for improved wear life of SKF bearing products. The specifications pertain to roughness and asperity slope effects, material hot hardness influence on surface fatigue, and the use of solid lubricating surface treatments. A value estimate of the benefits to SKF is not available.

One of the fluids tested at SKF, a synthetic hydrocarbon designated Mobil XRM 177, was developed in the 1950's by Mobil Oil Company in Paulsborough, New Jersey (44287). The Mobil fluid was not referred to as a lubricant prior to the SKF tests, which first established its lubricating properties. Mobil XRM 177 provided bearing wear life superior to any other fluid tested. SKF recommends it to bearing customers as the best known fluid lubricant. The fluid is currently used in military aircraft hydraulic systems and additional applications are quite probable as a result of the tests. Sales figures are not available from Mobil for this particular product.

Another NASA program which has produced important lubrication technology through testing is the development and production of gyroscopes by A.C. Electronics, a division of the General Motors Corporation, under contract (NAS 9-469) to Manned Spacecraft Center. Three of the inertial reference integrating gyroscopes produced by A.C. Electronics are used in the primary guidance system of each spacecraft. Another General Motors Division, New Departure-Hyatt (NDH), in Sandusky, Ohio (44284), received a subcontract from A.C. Electronics in 1962 to design and produce the ball bearings for the gyroscope spin axis.

Since the amount of lubricant is inversely related to the stability of the gyroscope, the bearing was required to have a long wear life with little lubrication. The combination of a microscopically rough bearing surface and very little lubricating fluid does not allow elastohydrodynamic (EHD) lubrication. Without EHD lubrication, the bearing surface deteriorates as microscopic metal pieces are spalled from it. The metal pieces act in the lubricating fluid to increase its torque which effects the precision of the gyroscope. NDH researchers conducted extensive tests while working on these technical problems. Analysis at NDH of the test results has generated significant insight into the relationships among (1) the surface finish of bearings, (2) lubricant behavior, and (3) bearing surface deterioration. A company spokesman

recently indicated that the NDH research facilities and technical expertise acquired during the NASA subcontract work have been used to create a new manufacturing process at NDH. The process has significantly increased the wear life of certain NDH ball bearings that are used in aircraft engines.

Control Numbers

Tech Brief Number: None
NASA Centers: Lewis Research Center and Manned Spacecraft Center
PATT Case Numbers: 44284, 44285, 44287
TEF Number: 339
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